LATE-TYPE SUPERGIANT STARS IN THE MAGELLANIC CLOUDS

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The work described in this thesis is that of the candidate. About most were made otherwise in the text. The candidate was partially involved in the observations on which Chapter 1 is based and the analysis of these particular observations was assisted but by the candidate in collaboration with Dr. A.B. Hyland. Chapters 2 and 3 have been prepared for publication as joint papers with Dr. A.B. Hyland.

To

Siew-Gim

[Signature]  
July, 19-?
The work described in this thesis is that of the candidate alone except where noted otherwise in the text. The candidate was partially involved in the observations on which Chapter 2 is based and the analysis of these particular observations was carried out by the candidate in collaboration with Dr. A.R. Hyland. Chapters 2 and 3 have been prepared for publication as joint papers with Dr. A.R. Hyland.

P. McGregor

July, 1981
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The infrared and optical properties of late-type supergiants in the central region of the 30 Doradus complex, in young Magellanic Cloud blue globular clusters and in galactic open clusters are investigated. The following observational differences are identified.

(1) The Magellanic Cloud supergiants are redder in (J-H)_0 and bluer in (H-K)_0 than galactic supergiants of the same luminosity. Synthetic broad band infrared colour calculations are used to show that this difference is due to the effect of weaker CN absorption in the Magellanic Cloud stars, predominantly in the H pass band. Similarly, the separation in the (J-H)_0 vs (H-K)_0 plane between luminosity class Ib and Ia supergiants in each galaxy is shown to be due to the stronger CN absorption in the more luminous stars.

(2) The 2.3 µm CO indices of the LMC and NGC 330 (SMC) supergiants are smaller than for galactic supergiants of the same (J-K)_0 colour by -0.04 and -0.1 mag, respectively.

(3) The TiO band strengths in the Magellanic Cloud supergiants are weaker than in galactic supergiants of the same (J-K)_0 colour.

(4) For (J-K)_0 colours greater than -1.0 mag, the Magellanic Cloud supergiants have bluer (V-K)_0 colours than galactic supergiants of the same (J-K)_0 colour. This difference is shown to be due to the effect of weaker TiO absorption on the V magnitude in metal deficient Magellanic Cloud stars with temperatures below -3800K.
The physical and chemical differences responsible for these observational differences are interpreted using synthetic spectrum analyses of the 2.3 µm CO bands, of the red TiO bands and of intermediate resolution blue spectra in the region of the G band. Heavy element abundances of \([A/H] = -0.5 \pm 0.2\) and \(-0.5 \lesssim [A/H] \lesssim -1.0\) are obtained for the LMC and NGC 330 (SMC) supergiants, respectively, in agreement with other abundance results for Population I objects in the Magellanic Clouds. Carbon is found to be depleted relative to the heavy elements in all the supergiants studied by \([C/A] = -0.6 \pm 0.2\). A mean microturbulent velocity of \(4.5 \pm 0.5\) km sec\(^{-1}\) for both the galactic and LMC samples is required to fit their 2.3 µm CO indices. A lower mean microturbulent velocity of \(2.5 \pm 0.5\) km sec\(^{-1}\) is required to fit the 2.3 µm CO indices for the NGC 330 (SMC) supergiants using a mean heavy element abundance of \([A/H] = -1.0\).

The blue globular cluster supergiants have luminosities consistent with the end-main sequence masses in each cluster \((-14M_\odot)\). The range in luminosity of stars on the giant branch of each cluster indicates that star formation has occurred over a time span of \(-10^7\) yr in these blue globular clusters.

The 30 Doradus region is shown to have undergone at least two bursts of star formation in the last \(-5 \times 10^7\) yr. The many similarities of the 30 Doradus central cluster and the slightly older blue globular clusters are noted. The prior condensation of a larger, more extended stellar association may be a common feature of all blue globular cluster formation histories.
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INTRODUCTION

I. GENERAL

As our closest neighbouring galaxies, the Magellanic Clouds present a unique opportunity to study processes of star formation, chemical enrichment, and stellar evolution in external, isolated galactic systems. The present chemical compositions of extreme Population I objects, and of the interstellar medium, in the Magellanic Clouds reflect the full history of such processes in these galaxies. A knowledge of these chemical abundances can therefore provide important information on the evolutionary processes that have occurred in the Magellanic Clouds.

Studies of a range of Population I objects have indicated that the Large Magellanic Cloud (LMC) is, in general, deficient in heavy elements relative to the Galaxy by a factor of 2-3, and that the Small Magellanic Cloud (SMC) is somewhat more metal poor, being deficient by a factor of 5-10 relative to the Galaxy (see e.g., van den Bergh 1975). Detailed stellar abundance determinations are difficult because they require high resolution spectra of quite faint objects. Analyses of this type have so far been restricted to a limited number of early-type stars, and have produced results which are generally in agreement with the above picture, although conflicting abundances have been derived for a few individual stars. Optical photometry on the other hand, has been less successful in elucidating relative differences between the intrinsic properties of early-type stars in these galaxies because the almost featureless spectra of early-type stars offer little at low resolution.
The late-type supergiants in the Magellanic Clouds are of reasonable brightness, easily identified, occur in large numbers and, in contrast to the early-type stars, contain a wealth of atomic and molecular spectral features which have significant effects on both broad- and intermediate-band photometry. In this thesis we address the problem of determining Population I stellar abundances in the Magellanic Clouds in a new way by comparing the observational properties of late-type supergiants in the Magellanic Clouds and in the Galaxy. By calibrating the photometric and spectroscopic differences that we find with changes in stellar atmospheric parameters, we derive relative chemical abundances for these stars.

This approach to Magellanic Cloud abundance analysis is similar to that used in recent studies of galactic globular cluster giant branch stars. Due to their smaller size and lower mass, the atmospheric parameters of the giant branch stars do not differ greatly from those of supergiants. For this reason important parallels exist between the giant and supergiant analyses.

The stars studied in this thesis have been largely restricted to the late-type supergiants that are members of young Magellanic Cloud blue globular clusters and to the supergiants in the immediate vicinity of the closely related object, 30 Doradus. In this way inferences can also be made concerning the formation and evolution of the systems to which these stars belong.

In the following we discuss the current status of young Population I research in the Magellanic Clouds and the relevance of the present work to late-type supergiant studies in general.
II. POPULATION I CHEMICAL ABUNDANCES

(a) Stellar Analyses

No definitive picture of Population I stellar abundances in the Magellanic Clouds has yet emerged from direct stellar analysis. This is largely due to the difficulties involved in analysing the spectra of very luminous supergiants and to the consequent lack of agreement reached by different workers for the abundances of individual stars. The results of these analyses are summarized in Table 1. In addition, Smith (1980) has determined mean calcium abundances of \([\text{Ca/H]} = -0.2 \pm 0.1\) for the LMC and \(-0.6 \pm 0.1\) for the SMC from samples of F supergiants. The conflicting abundances obtained by Przybylski and Wolf for the SMC star HD7583 exemplify the problem of interpreting these results. Przybylski (1979) has suggested that a considerable range in chemical abundance may exist among young stars in the LMC. The existence of such a spread in young Population I abundances is not confirmed by Cepheid variable studies or by HII region abundance determinations (see below).

Table 1

<table>
<thead>
<tr>
<th>Star</th>
<th>SpT</th>
<th>([\text{A/H]})</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>LMC</td>
<td>HD33579</td>
<td>A3Ia-0</td>
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<td>HD268759</td>
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<td>HD271182</td>
<td>F8Ia</td>
<td>+0.2</td>
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<td>HD270086</td>
<td>A1Ia-0</td>
<td>-1.0</td>
</tr>
<tr>
<td>SMC</td>
<td>HD7583</td>
<td>A0Ia-0</td>
<td>-1.0</td>
</tr>
<tr>
<td></td>
<td>HD7583</td>
<td>A0Ia-0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>HD5045</td>
<td>B3Ia</td>
<td>(\leq -0.6)</td>
</tr>
<tr>
<td></td>
<td>HD7099</td>
<td>B2.5I</td>
<td>(\leq -0.6)</td>
</tr>
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</table>
(b) **Cepheid Variables**

Cepheid variables provide an indirect means of determining relative stellar abundances through variations in two main Cepheid properties; (1) Magellanic Cloud Cepheids are bluer and (2) their period-frequency distributions displaced from those of galactic Cepheids.

The mean colours of Cepheid variables become progressively bluer in the order Galaxy, LMC, SMC. Martin, Warren and Feast (1979) measured an intrinsic colour difference between the Galaxy and the LMC of 0.05 mag in B-V. Gascoigne (1969) obtained a difference of -0.1 mag, to lower accuracy, in B-V between galactic and SMC Cepheids. Precise values for the intrinsic colour shifts are difficult to determine because mean colours are not currently available in sufficient numbers to accurately define the bands Cepheids from each galaxy occupy in the Period-Colour (P-C) diagram. Accurate reddening corrections for both galactic and Magellanic Cloud variables are also needed to determine accurate intrinsic colour differences.

The lower blanketing in metal deficient atmospheres (Bell and Rodgers 1969) and the dependence on metallicity of the location of the Cepheid instability strip in the log L-log $T_e$ plane (Iben and Tuggle 1975) both act to make the colours of metal deficient Cepheids bluer. The observed ranking in colour is, therefore, also a ranking in metallicity with metallicity decreasing in the sense Galaxy, LMC, SMC.

The Period-Luminosity-Colour (P-L-C) relation for the LMC is now well determined (Martin et al.) with the remaining scatter being of the order of the observational errors. Gascoigne (1974) demonstrated that the P-L-C relation was dependent on metallicity through the effects of blanketing on the colour term. Specifically, using the log $T_e$ vs (B-V)
relations of Bell and Parsons (1972), Gascoigne derived a theoretical
dependence of the colour coefficient in the P-L-C relation on metallicity.
Using the improved $\log T_e$ vs $(B-V)_o$ relations of Bell and Gustafsson
(1978), Gascoigne (1980) now finds the variation in the colour coefficient
to be small in stars of moderate metal deficiency but predicts large
variations in the constant term in the P-L-C relation. This dependence
suggests that a range in metal deficiency of the order of 0.5 dex would
produce a scatter in $M_V$ of the order of 0.3 mag; much larger than the
observed tight correlation when observational errors are considered.
This result points to the existence of a high degree of abundance
uniformity among LMC Cepheids.

The short period cut-off and period of maximum frequency in the
Cepheid period-frequency distribution (i.e. number of variables in a
given period range) both move to successively shorter periods in the order
Galaxy, LMC, SMC. The existence of Cepheid variables depends on the
degree of penetration of the Cepheid instability strip during loop
evolution in massive stars. Christy (1971) demonstrated that the difference
in short period cut-off was due to the dependence of loop length on
abundance. Lower heavy metal or helium abundance increases the loop length,
permitting shorter period Cepheids to occur. Robertson (1973) required
abundance differences in either helium or heavy elements between the SMC
and LMC of $\delta Y(SMC-LMC) = -0.083$ or $\delta Z(SMC-LMC) = -0.027$ to fit the observed
short period cut-offs. These calculations depend sensitively on the
stellar opacities and convection theory used. Becker, Iben and Tuggle
(1977) fit synthetic period-frequency distributions with $Z = 0.014, 0.016,$
and 0.03 for the SMC, LMC and Galaxy, respectively. These authors note
that the incomplete Magellanic Cloud sample and the approximate nature of
the evolutionary tracks adopted make the absolute values uncertain. The
technique is better suited to estimating relative mean values for $Z$. 
Thus the Cepheid variables allow young stellar populations to be ranked in order of abundance but our understanding of these variables is not yet adequate to utilize their mean properties to accurately determine absolute mean abundances. On the basis of present data, the mean properties of LMC and SMC Cepheids are consistent with the abundances derived by other methods for these galaxies. The Cepheid P-L-C relation does not appear to permit a spread in Population I abundances in the LMC of the magnitude suggested from direct stellar analyses.

(c) Emission Line Regions

Spectra of Magellanic Cloud emission line regions can be obtained more easily than stellar absorption line spectra, however, the analysis of emission line data is not without its difficulties and only allows determinations of light element abundances to be made. HII regions, supernova remnants (SNR's) and planetary nebulae have been studied in this way. The results (Table 2) are, once again, in general agreement with a greater abundance deficiency in the SMC than in the LMC. Planetary nebulae determinations should be viewed with some caution in this context since they may not be indicative of present day extreme Population I abundances in the Magellanic Clouds.

Discrepancies are apparent between HII region and SNR abundance determinations. These may be due to systematic errors in the HII region determinations, introduced through the widely adopted practice of neglecting line of sight temperature variations (Dopita, Mathewson and Ford 1977). The existence of such line of sight temperature variations has been predicted on theoretical grounds by Dopita et al. However, the most recent HII region determinations (Pagel et al. 1978), employing more careful analysis techniques, give results in reasonable agreement with previous HII region work.
Table 2

Emission Line Region Abundances*

<table>
<thead>
<tr>
<th></th>
<th>[N/H]</th>
<th>[O/H]</th>
<th>[Ne/H]</th>
<th>[S/H]</th>
<th>N(He)/N(H)</th>
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<tr>
<td>LMC</td>
<td>-0.83</td>
<td>-0.19</td>
<td>-0.61</td>
<td>-</td>
<td>0.084</td>
<td>Peimbert &amp; Torres-Peimbert (1974)</td>
</tr>
<tr>
<td>LMC</td>
<td>-1.13</td>
<td>-0.34</td>
<td>-0.91</td>
<td>-0.06</td>
<td>0.102</td>
<td>Dufour (1975)</td>
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<tr>
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<td>-0.31</td>
<td>-0.72</td>
<td>-0.01</td>
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<td>Aller et al. (1974)</td>
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<td>-0.4</td>
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<td>-0.72</td>
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<td>-</td>
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<td>Peimbert &amp; Torres-Peimbert (1976)</td>
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<td>-0.83</td>
<td>-</td>
<td>Pagel et al. (1978)</td>
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<td>-0.17</td>
<td>-0.02</td>
<td>-0.65</td>
<td>-</td>
<td>-</td>
<td>Peimbert &amp; Torres-Peimbert (1977)</td>
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<td><strong>Planetary Nebulae</strong></td>
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<td>LMC</td>
<td>-0.39</td>
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<td>-</td>
<td>0.09</td>
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<td>-0.45</td>
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<td>0.12</td>
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<td>-1.63</td>
<td>-1.17</td>
<td>-1.36</td>
<td>-</td>
<td>-</td>
<td>Dopita et al. (1977)</td>
</tr>
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</table>

* Adopted logarithmic solar abundances of N, O, Ne, and S are 7.93, 8.77, 8.55, and 7.21, respectively (log N(H) = 12.00).
HII region results suggest oxygen is deficient by a factor of 5-6 relative to Orion in the SMC, and deficient by a factor of 2 relative to Orion in the LMC. Nitrogen is deficient relative to oxygen by a factor of 3-4 in both Clouds. HII region spatial abundance gradients are absent from both Clouds, in agreement with the Cepheid variable star results.

Further stellar analyses are therefore required in order to test the suggestion, based on present direct stellar analyses, that an abundance spread exists among Population I Magellanic Cloud stars.

III. LATE-TYPE SUPERGIANT STUDIES

Late-type supergiants have been recognized in the Magellanic Clouds since the infrared objective prism survey of Westerlund (1960, 1964) and the early determinations of young cluster and association colour-magnitude diagrams (see below). Extensive catalogues of LMC late-type supergiants have recently been published (Sanduleak and Davis-Philip 1977, Westerlund et al. 1978, Westerlund, Olander and Hedin 1981). A large percentage (~20%) of these catalogued LMC supergiants can be identified with known variable stars (Sanduleak and Davis-Philip 1977). Lloyd Evans (1971) found that ~15% of the SMC M supergiants studied by him were large amplitude variables, with amplitudes ≥ 4 mag. Such variables are rare in the Galaxy and the LMC and their occurrence in the SMC may be prompted by the low metallicity in that galaxy (van den Bergh 1975).

Detailed study of the Magellanic Cloud late-type supergiants commenced only recently. Infrared photometry of 38 Magellanic Cloud late-type variable supergiants has been presented by Glass (1979). Absolute bolometric magnitudes ranged up to -9 mag for the LMC sample and -8.5 mag for the SMC sample. In both samples the giant branch became bluer at higher luminosities. Red supergiant variables were shown to
exist at earlier spectral types in the SMC than in the LMC, probably also
due to the lower metallicity in the SMC.

Humphreys has made optical spectroscopic and photometric studies of
M supergiants in the LMC (Humphreys 1974, 1979a) and in the SMC (Humphreys
1979b). Although the spectra are not significantly different (at 90Å/mm)
from the galactic standards used to classify them, a progressive shift in
the late-type supergiant spectral type distribution towards earlier spectral
types is apparent as one passes from the Galaxy to the LMC and to the SMC.
The displacement is small between the Galaxy and the LMC, with spectral
type assignments as late as M4 being possible in both galaxies. However,
the displacement between the SMC and the Galaxy is considerable; of 25 SMC
M supergiants classified by Humphreys (1979b), none could be classified
later than M1. Since the MK spectroscopic temperature classification is
based primarily on TiO band strengths, abundance deficiencies in the SMC
may be directly responsible for the earlier spectral types through the effect
of lower abundance on the atmospheric TiO opacity. However, Humphreys has
stressed that the spectra are not peculiar and show no striking indication
of metal weakness. This fact argues against such an interpretation. An
alternative explanation is that the late-type supergiants occur at hotter
temperatures in the SMC than in the Galaxy. Such a situation could con­
ceivably be due to the effect of lower abundance on the evolutionary tracks
of massive stars. In this case spectroscopic differences between SMC and
galactic supergiants of the same colour (i.e., temperature) would not
necessarily be present. Humphreys found no differences in the intrinsic
optical colours of galactic and Magellanic Cloud supergiants of a given
spectral type, in agreement with this interpretation. It should, never­
theless, be noted that infrared photometry of Humphreys' stars would be
required to convincingly separate temperature difference effects from
direct abundance effects.
Humphreys has also showed that despite the probable abundance differences, the brightest M supergiants in the Galaxy, LMC and SMC all have absolute visual magnitudes of \( M_V = -8.0 \) mag. Thus evidence from the Magellanic Clouds supports the suggestion of Sandage and Tammann (1974) that M supergiants can be used as extragalactic distance indicators.

IV. THE 30 DORADUS COMPLEX

The 30 Doradus Nebula is a giant HII region of unequalled dimensions in the LMC. However, of greater interest in relation to the present work is the existence, within the 30 Doradus complex, of a central compact star cluster with many features in common with the young Magellanic Cloud blue globular clusters. This central region of the complex contains late-type supergiant stars, younger newly-formed massive Wolf-Rayet stars and, from its optical appearance, is very probably also a site of on-going star formation in the LMC. In addition to their intrinsic interest, the late-type supergiants in the immediate vicinity of the 30 Doradus cluster have been included in the present study in order to investigate their relationship to this central cluster.

Shapley and Paraskevopoulos (1937) first noted the concentration of blue stars at the centre of the 30 Doradus Nebula. Feast, Thackeray and Wesselink (1960) classified nine of these stars as Wolf-Rayet stars of the nitrogen sequence and one as 08. Feast (1961) reported the central object of the cluster (R136; WN + 0:) to be extended on a scale of \(-2\) arcsec. This object is most probably a compact cluster of stars with a luminosity equivalent to \(-60\) 0 stars (Walborn 1973, Walraven and Walraven 1975). Westerlund (1961) measured a colour-magnitude diagram for stars in the region of the 30 Doradus cluster. The diagram showed a strong, broad, vertical main sequence of blue stars. Significant variations in interstellar reddening were apparent from the width of the main sequence \((-0.6\) mag in B-V). Westerlund (1964) identified a large number of late-
type supergiants in the general vicinity of the 30 Doradus Nebula. The nebula was shown to lie in the midst of a much larger young star cloud, with an M supergiant density of \( \sim 50 \) M stars per square degree. No late-type supergiant stars were detected in the immediate vicinity of the central cluster where strong nebula emission inhibited optical investigations.

Hyland, Thomas and Robinson (1978) overcame this difficulty by surveying the central 12 arcmin of the nebula at infrared wavelengths. Among the 2 \( \mu \)m sources they detected were four WN stars and ten M supergiants, implying an M supergiant density of \( \sim 250 \) M stars per square degree in the central region. This fact demonstrated that the late-type supergiants of the outer region also extended to the central region of the nebula and that their spatial density actually increased towards the centre. Thus the central cluster of younger, more massive blue stars (with ages of \( \sim 10^6 \) yr) was seen to have formed in the midst of a region which had itself only recently undergone star formation (the M supergiants have ages of \( \sim 10^7 \) yr).

The latter discovery leads one to investigate the star formation mechanism operative in the 30 Doradus central cluster, and by implication possibly also in other blue globular-type clusters in the Magellanic Clouds.

In the Galaxy, OB star formation occurs at the edges of molecular clouds. Elmegreen and Lada (1977) have expounded a theory of sequential formation of OB stars where ionization-induced shocks from recently formed OB stars compress adjacent regions of a molecular cloud and so bring about the collapse of a further generation of OB stars. The sequential nature of galactic OB star formation is suggested by the existence of definite subgroups in galactic OB associations (Blaauw 1964) which can in some cases be associated with a definite temporal sequence terminating in a region of active star formation at an HII region/molecular cloud interface. Supernova-induced shocks, stellar wind-induced shocks, density wave shocks and cloud-cloud collisions may also induce star formation. Processes of
massive star formation in the Galaxy have recently been reviewed by Lada, Blitz and Elmegreen (1978).

Little is known of the star formation mechanisms operative in the Magellanic Clouds. The Magellanic Clouds have, so far, only been subjected to cursory examinations for the existence of molecular clouds. One such cloud has been detected ~40 arcmin south of 30 Doradus, associated with the emission region N159 (Henize 1956). Star formation of the type found in the Galaxy appears to be occurring in this region (Gatley et al. 1981), but no H$_2$CO or CO emission has been detected from the 30 Doradus region (Huggins et al. 1975, Whiteoak and Gardner 1976). This is in agreement with the far-infrared results of Werner et al. (1978) which also suggest the absence of any large molecular cloud in the 30 Doradus region. Thus star formation in the 30 Doradus complex may not follow the same scenario occurring in galactic OB associations. The existence of young blue globular clusters in the Magellanic Clouds, especially in the outer low density regions of these galaxies, is clear evidence that the star formation histories in these galaxies differ in significant respects from that found in the Galaxy (cf., Freeman 1977).

V. BLUE GLOBULAR CLUSTER RESEARCH

Modern study of the Magellanic Cloud blue globular clusters began with the discovery of a number of classical Cepheid variables in and near the apparently globular cluster NGC 1866 in the LMC (Shapley and McKibben-Nail 1951). Since classical Cepheids are Population I objects in the Galaxy, the stellar population of this cluster had, in effect, been shown to be unlike that in any galactic globular cluster. The generality of this discovery was soon demonstrated when Gascoigne and Kron (1952) published integrated colours for 21 star clusters of globular appearance
in the Magellanic Clouds. These clusters separated about equally into red and blue groups, with the colours of the red group resembling those of normal galactic globular clusters and the colours of the blue group, amongst which was NGC 1866, resembling those of the young galactic open clusters.

Arp (1959a) produced the first colour-magnitude diagram (CMD) of a blue globular cluster, NGC 458 in the SMC. The diagram broadly resembled that of the Pleiades but differed in that it possessed a large number of yellow giants with B-V of only 0.5 to 0.9 mag, it had a narrow well-defined Hertzsprung gap and showed a discontinuity of about one magnitude in luminosity between the top of the main sequence and the blue giants. Arp attributed these differences to differences in chemical composition between the NGC 458 stars and the Galaxy and assigned an age of $-2 \times 10^7$ yr (similar to the Pleiades) to the cluster. The same general CMD morphology, this time resembling h & χ Persei, was found for the brighter SMC blue globular cluster, NGC 330 (Arp 1959b). This diagram confirmed the results found for NGC 458 and showed that the differences responsible extended to stars as young as only a few by $10^6$ yr. The latter result contrasted with studies of the brightest Magellanic Cloud stars of similar age (Feast et al.) which had found no evidence for metal deficiency.

It was soon shown that in these particular cases the larger numbers of SMC red supergiants could possibly be explained by the greater richness of the SMC clusters and that the break between main sequence and blue giant stars was in fact a feature common with young galactic clusters (Feast 1960). Nevertheless, major differences do exist between the CMD's of young galactic and Magellanic Cloud clusters and comparisons with theoretical evolutionary tracks for metal deficient massive stars (Hagen and van den Bergh 1974; Robertson 1974b) have confirmed that these differences are due to metal abundance differences between the two
galaxies. The distribution and number of late-type cluster supergiants are among the most apparent of these CMD differences. The red giant branch in Magellanic Cloud clusters is generally brighter and bluer than in galactic clusters of the same age (Hagen and van den Bergh 1974), with the largest difference being for the SMC clusters.

CMD's for a large number of young Magellanic Cloud clusters have been measured (e.g., Woolley 1960, Westerlund 1961, Hodge 1961, 1963, Arp and Thackeray 1967, Tift and Connolly 1973, Hodge and Flower 1973, Robertson 1974a, Walker 1974, Flower and Hodge 1975, Connolly and Tift 1977), making the late-type supergiants in these globular clusters the most studied as well as being the most homogeneous sample of late-type supergiants in the Magellanic Clouds. Many cluster CMD's resemble those of their surrounding fields, indicating that many, if not all, of these clusters have formed as part of the condensation of larger star systems (Robertson 1974a and references therein).

The richness, low reddening and known distance of the blue globular clusters make them ideal for comparison with theoretical evolutionary tracks and theories of mass loss in massive stars. It is apparent from such comparisons that a continuum of blue globular cluster ages exists from \(-10\) yr for NGC 1831 to \(-10\) yr for NGC 2100, 2004 and 330 which have CMD's resembling that of h and x Persei. Main sequence turnoff masses range from \(-20\) M\(_\odot\) in the younger clusters to \(-5\) M\(_\odot\) in the older clusters. Galactic orbital velocities for the LMC blue globulars follow the same rotation curve as defined by extreme Population I objects (Andrews and Lloyd-Evans 1972). Their physical association with other very young objects is therefore confirmed.

The first suggestion that the Magellanic Cloud blue globulars were actually young globular clusters is due to Woolley (1960). Dynamical studies of the blue globular clusters were nevertheless necessary to prove
their globular nature. Surface brightness distributions for several clusters have been shown to be well fitted by the same dynamical King models applicable to old galactic globular clusters (Freeman and Gascoigne 1971, Freeman 1974, Chun 1978). The Magellanic Cloud blue globulars are therefore truly the young globular clusters envisaged by Woolley. The agreement obtained with dynamical King models suggests that the blue globular clusters are dynamically relaxed systems yet in all cases investigated the dynamical crossing time < the cluster age < the theoretical relaxation time. This property is most likely related to the method of blue globular cluster formation in the Magellanic Clouds. Dynamical cluster masses derived from the models are in the range $10^4 - 10^5 M_\odot$. These masses are comparable to those of low mass galactic globular clusters. Freeman (1977) also finds that the slope of the initial mass function varies from cluster to cluster with a range of $0.0 \leq x \leq 2.5$ ($x = 1.35$ for the Salpeter mass function). This range is most likely to also be related to the method of formation of blue globular clusters in the Magellanic Clouds and has important implications for theories of both globular cluster formation and star formation in the early Galaxy.

NGC 330 in the SMC is the best studied example of the Magellanic Cloud blue globular clusters. The cluster contains a large number of main sequence Be stars in a band between $M_v = -4.4$ and $-3.6$ (Feast 1972). In this respect the cluster is similar to the extreme nucleus of X Persei. The Be phenomenon is generally attributed to stellar rotational instability. Thus the absence of non-emission stars in the Be region of the NGC 330 CMD indicates that most main sequence stars in the cluster are fast rotators. Feast (1979) classified the spectra of eight late-type supergiants in the cluster and found spectroscopic evidence for metal deficiency in that CN appeared weak and H appeared strong. All eight supergiants were classified
as G5Ib which is much earlier than their optical colours (B-V = 1.3-1.6) suggest. Janes and Carney (1977, 1980) claim that the DDO indices δ3842 and δCN for four stars in the cluster both indicate [Fe/H] < -1.3. If confirmed this result will be of great significance because it suggests that gas clouds with metallicities significantly lower than is believed to be normal for the interstellar medium in the SMC have survived in that galaxy until very recently.

Feast and Black (1980) measured a dispersion of 2 km s⁻¹ in the velocities of 25 NGC 330 stars. On this evidence the cluster appears to lack any spectroscopic binaries, as may be expected from the high incidence of Be stars. In contrast, Janes and Carney (1980) find a velocity dispersion of -100 km s⁻¹ from an integrated cluster spectrum, suggesting that the cluster as a whole is in rapid rotation. These two results are in conflict and the matter remains to be resolved.

In summary, the blue globular clusters in the Magellanic Clouds have been shown to be dynamically like the old globular clusters in the Galaxy but to have ages in the range 10⁷ - 10⁸ yr. The existence of these young, true globular clusters in the Magellanic Clouds, but not in the Galaxy, is one of the most fundamental differences between these galaxies. The colour-magnitude diagrams for the Magellanic Cloud clusters differ from those of galactic clusters of the same age predominantly in the colour, luminosity and number of their late-type supergiants. Comparisons with theoretical evolutionary tracks for metal deficient massive stars indicate that these differences are due to heavy metal deficiencies in the Magellanic Cloud clusters. Initial mass functions for these clusters are known to vary over a large range. NGC 330, the brightest SMC blue globular, remains an important test case in blue globular cluster studies
since it is bright and populous and its CMD characteristics are extreme, its abundance deficiency may be large and there remains controversy over the orbital velocities of its members.

VI. OUTLINE OF APPROACH

From the foregoing, it can be seen that a study of the late-type supergiant stars in the Magellanic Clouds can address a number of problems related to both young Population I objects in the Magellanic Clouds and to late-type supergiants as a separate class of objects. These problems can be briefly summarized as follows:

(1) What are the observational properties of Magellanic Cloud late-type supergiants and how do they compare with the observational properties of similar stars in the Galaxy?

(2) What are the chemical abundances of the Magellanic Cloud late-type supergiants? Do they indicate the presence of a range of abundances among young Population I objects in either of the Magellanic Clouds?

(3) Has the presence of M supergiants in regions of recent star formation (such as the 30 Doradus region) influenced the nature of recent star formation in these regions?

(4) In what evolutionary state are the Magellanic Cloud late-type supergiants and to what extent has mass loss influenced their evolution?

In this thesis a variety of observational techniques have been used to address these problems. Infrared photometry has been obtained as basic data. This is used to determine effective temperatures and luminosities for the late-type supergiants which are required for both the determination
of chemical abundances and for comparison with predictions from stellar evolution theory. The techniques available to us for abundance analysis are restricted by the faintness of the Magellanic Cloud supergiants. With average apparent visual magnitudes in the range $V = 13.0 - 13.5$ mag, they lie beyond the range of high resolution spectroscopic analysis. Low resolution optical and infrared photometric and spectroscopic data have therefore been obtained of the prominent molecular features (i.e., TiO and CO bands) which occur in late-type supergiant spectra. The strengths of these features have been used in comparison with theoretically derived synthetic spectra to determine chemical abundances. Higher resolution spectra in the blue spectral region have also been obtained and provide an independent check on the low resolution results.

The following chapters of this thesis are set out as follows:

In Chapter 2, the M supergiants in the vicinity of the 30 Doradus complex are studied and their significance for the star formation history of the region is discussed. Infrared observations of late-type supergiants in blue globular clusters are presented in Chapter 3. The infrared properties of these stars are compared with those of galactic supergiants and inferences made about the chemical abundances and evolutionary status of the blue globular cluster stars. Synthetic spectra of the 2.3 $\mu$m CO bands in late-type stars are used in Chapter 4 to interpret observational CO band indices for the Magellanic Cloud supergiants. Theoretical analyses of the TiO $\gamma(\Delta v=0)$ and $\gamma'(\Delta v=0)$ bands in the red spectral region are presented in Chapter 5 and are used to interpret observational data for these features. Finally, in Chapter 6, intermediate resolution optical spectra in the region 4200 - 4600$\AA$ of galactic and Magellanic Cloud late-type supergiants are compared and discussed.
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CHAPTER 2

INFRARED STUDIES OF THE TWO STELLAR POPULATIONS IN 30 DORADUS

P.J. McGregor and A.R. Hyland

ABSTRACT

Broad band J, H, and K magnitudes are presented for 33 blue and red supergiant stars within the central 12 arcmin of the 30 Doradus complex. Band strength indices for the 2.3 μm CO bands of 10 of the red stars are also given. These more detailed data confirm an earlier conclusion that at least two bursts of star formation have occurred in the 30 Doradus region in the last \(-5 \times 10^7\) yr, with the most recent event occurring \(\leq 10^6\) yr ago.

Mass loss rates derived for the 30 Doradus Wolf-Rayet stars are comparable with the highest rates found by other workers for galactic Wolf-Rayet stars. These high mass loss rates place severe limits on the age of the blue population.

The broad band colours of the late-type supergiants differ from the colours of galactic stars of the same luminosity. The CN molecular opacity is shown to be important in determining the infrared colours of these luminous supergiants and to be sensitive to metal abundance. The observed differences can therefore be plausibly interpreted as evidence for metal deficiency in the 30 Doradus supergiants. These late-type supergiants form a well defined sequence in the (CO)_o vs (J-K)_o plane above and parallel to the mean galactic giant line. At a given effective temperature, their CO band strengths are weaker than those of the limited number of galactic supergiants for which published data are available.
A discussion of the possible causal relationship between the two stellar populations is given in terms of recent theories of OB star formation.

I. INTRODUCTION

The exceptional object, 30 Doradus, is unique in the Large Magellanic Cloud (LMC) in many respects, among which are the extent of its emission nebulosity (Meaburn 1979) and its concentration of extremely luminous Wolf-Rayet stars. The unusually high nebular luminosity (Faulkner 1967) and large gas velocities (Smith and Weedman 1972) are powered by these and other young stars which form a central compact cluster. The Wolf-Rayet stars have been the subject of several investigations at optical wavelengths in the past (Feast 1961; Westerlund and Smith 1964; Smith 1968), with the number now identified being -15 (Feast, Thackeray and Wesselink 1960; Melnick 1978; Azzopardi and Breysacher 1979). Based on a variety of observations (Elliott et al. 1977; Werner et al. 1978; Mills, Turtle and Watkinson 1978; de Boer, Koornneef and Savage 1980), the present structure of the 30 Doradus Nebula appears to be that of an ionization "blister" (Israel 1978) in which the central star cluster has formed on the front face of a large neutral cloud, causing the ionization region associated with the early-type cluster stars to expand predominantly in a direction away from the cloud.

In view of the extreme youth of this stellar population, the unexpected discovery of a further, apparently older, population of M supergiants in the same region as the young population (Hyland, Thomas and Robinson 1978; HTR) raises questions of the origin of the emission nebula and of the possible causal relationship between the M supergiant population and the younger population characterized by the Wolf-Rayet
stars. The theories of sequential formation of OB associations through ionization-induced shocks (Elmegreen and Lada 1977) and supernova events (Herbst and Assousa 1977) are of interest in this context since they have attained some degree of success in the Galaxy. HTR, however, showed that the ages of the two populations in the 30 Doradus region placed crucial limits on the time scales involved. In this paper we investigate the two stellar populations of the 30 Doradus region in more detail to gain further insight into the nature of these populations and the relationship which may exist between them.

The compact central cluster of 30 Doradus has several characteristics in common with the slightly older blue globular clusters in the Magellanic Clouds; (1) the physical sizes of the 30 Doradus cluster and, for example, the nearby blue globular cluster NGC 2100 are comparable (see inset to Fig. 1), (2) the total mass of the 30 Doradus cluster of \(-4 \times 10^5 M_\odot\) (Churchwell 1975), within the errors, is of the same order as the mass of \(5 \times 10^4 M_\odot\) found for NGC 2100 (Ford 1970), (3) the ages of the 30 Doradus Wolf-Rayet stars (-10^6 yr) are consistent with the cluster being at an earlier stage of development than the youngest identified blue globular clusters, such as NGC 2100 (-10^7 yr old), (4) the 30 Doradus cluster is very centrally concentrated although the presence of several very luminous stars acts to camouflage this property to some extent. Such an appearance is not unlike our expectations for a globular cluster of this age. If the 30 Doradus central cluster is indeed a blue globular cluster it may be of great dynamical interest since it may become the first identified blue globular cluster with an age less than its dynamical crossing time (the mean dynamical crossing time for blue globular clusters is \(-5 \times 10^6\) yr (Freeman 1980)). Investigations of the 30 Doradus complex have added significance in this context.
The study of the M supergiant population in 30 Doradus at infrared wavelengths allows full advantage to be taken of the well known Magellanic Cloud characteristics of low foreground extinction and a well determined distance to derive precise values for their intrinsic properties. Photometric studies of galactic M supergiants in the literature are few in number and have suffered from the usual problems associated with high galactic extinction and distance uncertainties. The present study of the Doradus M supergiants represents the first step in a larger program to define the intrinsic infrared properties of the M supergiant class of objects. Due to the scarcity of intrinsic infrared data for galactic M supergiants, comparisons are also made with the infrared properties of galactic globular cluster late-type giant stars which have similar atmospheric parameters.

The observations presented in this paper are described in §II. The intrinsic parameters of stars in both populations are derived in §III, followed by a discussion of the results which relate to the complex as a whole. In §IV we discuss the two populations separately while the relationship between these two populations and the implications for the formation of the complex are discussed in §V.

II. OBSERVATIONS

Broad band J, H, and K photometry has been measured for thirty-three stars within the central 12 arcmin (-200 pc) of the 30 Doradus complex. Twenty-two of the objects were identified in the 2 μm survey of the 30 Doradus region of HTR. The remaining objects consist of previously identified early-type stars (Feast, Thackeray and Wesselink 1960), as well as some otherwise unstudied objects which were not detected in the infrared survey. Carbon-monoxide band strengths have been measured for ten of the
M supergiants in the sample from high signal to noise, low resolution 2 \( \mu \)m spectra. The photometric observations were obtained using the Mount Stromlo Observatory (M.S.O.) infrared photometer on the 3.9 m Anglo-Australian Telescope (A.A.T.) during the summers of 1976 and 1977. Most measurements were made using a 10 arcsec cooled aperture with a beam separation of 26 arcsec in an E-W direction. Larger apertures were employed on a few occasions of poor seeing. During the 1976 season the detector used was a liquid-nitrogen cooled PbS photoconductor. This had been replaced by a solid-nitrogen cooled InSb detector by 1977.

The observational technique and standardisation of the broad band (JHK) photometry were identical to those described by Mould and Hyland (1976); the photometry is thus on the system defined by Glass (1974). Recently, however, the Anglo-Australian Observatory (A.A.O.) infrared photometer has been commissioned; this uses a set of filters which more closely matches the J and K definitions of the original Johnson (1965) system than the Glass/M.S.O. system. The transformations between the Glass/M.S.O. system (G/M) and the A.A.O. system have been determined to be

\[
J_{AAO} = J_{G/M} + 0.07 (J-H)_{G/M}
\]

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H_{AAO} = H_{G/M}
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K_{AAO} = K_{G/M}
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by simultaneous observations in each system of blue and red stars covering the range 0 < J-H < 2.2. [We note that such transformations are similar to those determined between the Harvard and CIT photometric systems (Frogel et al. 1978). The former closely matches the original Johnson system, while the latter has similar filter characteristics to the M.S.O. system.]
The above transformations have been applied to all data presented in Table 1 and to all the data of Glass (1979) which are discussed in this paper. In this way the published photometry is placed on a system which is as close as possible to the original Johnson system. However, it should be noted that many of the results obtained in this paper are independent of the details of these transformations.

The 2 µm spectra of the late-type supergiants were obtained on the A.A.T. in February 1981 using a circular variable filter with a resolving power of 120 in the A.A.O. infrared system (Barton and Allen 1980). In addition, a 2 µm spectrum of the 30 Doradus central object, Dor IR 15, was obtained in March 1980 using the same A.A.O. photometer but with a circular variable filter having a resolving power of 60. The aperture and beam separation parameters in both cases were 7 arcsec and 12 arcsec, respectively. The direction of chop was generally N-S but was set to E-W for a few objects to avoid nearby stars. All observations of the program objects were made relative to BS 2015 which was observed before and after each object so as to minimize atmospheric corrections. All the 2 µm spectra of Doradus late-type supergiants exhibit strong absorption longward of 2.3 µm due to the first-overtone CO bands (Fig. 5). Dor IR 6 shows definite evidence of water-vapour absorption shortward of 2.1 µm. Weaker water-vapour absorption may be present in the spectrum of Dor IR 23. A CO index has been measured from the CVF spectra presented in Figure 5 by comparing the continuum region from 2.14 µm to 2.26 µm (Fig. 5, region A) with the absorption region from 2.32 µm to 2.42 µm (Fig. 5, region B).

The CO index \( (\text{CO}_{\text{CVF}}) \) is defined to be the ratio of the means of region A and region B expressed in magnitudes. Comparisons of indices obtained in this way from similar spectra of giant stars in \( \omega \) Cen with photometric
FIG. 1 - Identification Chart for the 30 Doradus supergiants.
The 30 Doradus photograph has been reproduced from a plate taken by Dr. B.E. Westerlund at the Newtonian focus of the Mt Stromlo 74" telescope through an interference filter with peak transmission at 5350 Å and half width of 110 Å. The photograph originally appeared in I.A.U. Symposium 24, p.353 (1966) and is reproduced here with the kind permission of Dr. Westerlund. The inset is a reproduction from the ESO blue sky survey of the LMC blue globular cluster NGC 2100 which lies -15 arcmin east of 30 Doradus. NGC 2100 and the 30 Doradus region are shown at the same scale to emphasize the similarities between the central 30 Doradus cluster and the slightly older blue globular cluster. The cross labelled SNR marks the location of the supernova remnant N157B.
narrow band indices for the same stars (Persson et al. 1980) showed the transformation between CO indices on our CVF system and the system of Frogel et al. (1978) (CO$^F$) to be

$$\text{CO}_F = 0.96 \text{CO}_{CVF}.$$ 

All CO indices presented in this paper have been transformed to the Frogel et al. (1978) system using the above transformation.

Table 1 contains the observational data for the Doradus stars. Right ascensions and declinations for the Doradus stars, as taken from the dials of the A.A.T. to an accuracy of ±3 arcsec, are given in columns (2) and (3) of Table 1. The identifications are marked in Figure 1. The transformed K magnitudes, J-K and H-K colours, number of observations of each object, and CO indices are given in columns (4) through (8). Spectral types, their sources, and optical photometry, and its sources, are given in columns (9) and (10), and (11) through (13), respectively.

(a) **Photometric Errors**

Errors in the photometry reported in this paper are a combination of statistical errors and those associated with repeatability of the standards. In nearly all cases statistical errors in the photometry were ≤ 0.01 mag at all wavelengths, with a few in the range 0.01 < E < 0.02. Errors are explicitly shown in Table 1 for those objects where E > 0.02. Errors estimated from repeatability of the standard stars were ~0.02 mag at K, and 0.02 mag for the colours J-K and H-K. It appears on the basis of repeated observations that at least two of the M supergiants (Dor IR 7 and 10) in our program exhibit variability at the 10% level. Mean values for their magnitudes and colours are given in Table 1.
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</table>

Notes to Table 1

SpT References

FTW Feast, Thackeray and Wesselink (1960)
T This paper, from 110 /,mm spectra obtained on the 74" telescope at Mt Stromlo.
HTR Hyland, Thomas and Robinson (1978)
S Smith (1968)

V, B-V References

1 Isserstedt (1975)
2 WS Westerlund and Smith (1964)
3 Westerlund (1961)
4 Wa Walborn (1977)

Notes (*)

2 Foreground star (Fehrenbach and Duflot 1970)
3 6m emission
20 Me I emission
22 Foreground star (Fehrenbach and Duflot 1970)
23 Double, both type M, separation 6 arcmin W-S, photometry of pair, southern source
24 M may brighter at K
29 Faint optically, implying large reddening
(b) Photometric Effects of Nebula Emission and Background Cluster Emission

The field in the central 3 arcmin (diam) of 30 Doradus is both crowded and contains strong nebular emission. It has therefore not been possible, despite precautions taken in the placement of the sky beams, to completely cancel all effects of the background in this central region. These effects are, however, small and do not affect any conclusions reached in this paper.

Most infrared photometry is carried out in a dual beam mode in which the source is compared with background emission on either side of it. Near the core of the 30 Doradus cluster, this is both impractical and likely to lead to gross errors since both sky beams would lie outside the region of high background emission. Consequently for those objects on the definitely sloping background within 2 arcmin of the central source (Dor IR 15) single beam measurements were made in which both reference sky beams were located on the same lower background side of the source. In this mode the chopped star/sky signal is compared with a chopped sky/sky signal on the lower background side. It can easily be shown that if the background slope is constant, the magnitudes are correctly measured; only changes in slope between the beams significantly affect the measurements. Observations were limited to those stars for which sky positions free of resolved stellar objects could be found.

The multiaperture photometry of Glass (1972) has been used to compute the effect of background radiation on our results. His measurements of the background and our observations of individual stars, together with the numbers of resolved optical images in the central region of the cluster, suggest that approximately 2/3 of the emission comes from the unresolved background. We have computed the effect of background on the measurements
of stars situated at 42" from the cluster centre, for the case of an 11.0 mag (at K) blue star (e.g., Dor IR 30) and a 10.4 mag (at K) M star (e.g., Dor IR 25). For the M star at least this is an unrealistic worst case since the faintest red star in the central region (Dor IR 18) is sufficiently bright that nebular emission will have no effect on its infrared photometry. The corrections to the magnitudes and colours in the two cases are given in Table 2. It can be seen from these results that only the faint central stars Dor IR 16, 17 and 32 are likely to be affected in any significant way. We note that none of the conclusions of this research depend upon observations of these 3 objects. Dor IR 14, 28, 30, 31 and 34 are likely to have had their K magnitudes measured too bright by -10%, but their colours should be good to -2%.

Table 2

Effects of Background Radiation in the Central Region

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<th>J</th>
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<th>H</th>
<th>F$_{1.6 \mu m}$ (mJy)</th>
<th>K</th>
<th>F$_{2.2 \mu m}$ (mJy)</th>
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<td>$\Delta (H-K)$ = -0.03</td>
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<td>$\Delta (H-K)$ = 0.02</td>
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III. ANALYSIS

(a) Reddening Correction, Bolometric Correction and Effective Temperature

Although the foreground reddening to the Magellanic Clouds is low, it is clear that large spatial variations will exist in the reddening experienced by individual stars embedded in LMC HII regions. The nature of the interstellar extinction in the central region of the 30 Doradus complex and its effects on the conclusions of this paper are discussed in Appendix I. As a first-order approximation we have adopted the spatial distribution of nebular extinction in 30 Doradus found by Mills, Turtle and Watkinson (1978) from a comparison of radio and Hβ isophotes. For stars outside the region covered by their Figure 5 a nebular extinction corresponding to the lowest contour level has been assumed. A foreground visual extinction of 0.2 mag was added to each value, as recommended by Mills et al. The extinction within 30 Doradus has been assumed to be anomalous in the sense found in other HII regions (e.g., η Carina, Herbst 1976) and a ratio of total to selective extinction (R = Av/E(B-V)) of 5 has been used. As discussed in Appendix I it was further assumed that the anomaly affects only the B filter while the infrared and visual extinction follow the normal galactic law (Lee 1970). The CO indices have been dereddened using $E(CO_p) = -0.15 E(H-K)$ (Jones et al. 1980), however in no case did the correction exceed 0.02 mag. The distance modulus to the eastern side of the LMC was taken to be 18.6 (Gascoigne and Shobbrook 1978). The adopted visual extinction and dereddened colours and magnitudes are given in columns (2) to (9) of Table 3.

Bolometric corrections and effective temperatures have been estimated in different ways for the blue and red stars. The bolometric corrections for Wolf-Rayet stars are not well known. For the purpose of including them in Figure 2, approximate bolometric magnitudes for the
| No. | $g_g$ | $g_o$ | $g_{(2-K)_o}$ | $g_{(3-K)_o}$ | $g_{(4-K)_o}$ | $g_{(5-K)_o}$ | $g_{(6-K)_o}$ | $g_{(7-K)_o}$ | $g_{(8-K)_o}$ | $g_{(9-K)_o}$ | $g_{(10-K)_o}$ | $g_{(11-K)_o}$ | $g_{(12-K)_o}$ | $g_{Log T_g}$ |
|-----|------|------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------|
| 1   | 0.20 | 8.66 | 1.15          | 0.24          | 0.28          | 2.8           | -             | 7.14          | 3.51          |               |               |               |               |                |
| 2   | 0.20 | 9.13 | 1.19          | 0.21          | 0.29          | 2.9           | -             | 6.57          | 3.49          |               |               |               |               |                |
| 3   | 1.07 | 9.28 | 1.04          | 0.19          | 0.25          | 2.7           | -             | 6.62          | 3.54          |               |               |               |               |                |
| 4   | 0.69 | 8.83 | 0.24          | 0.12          |               | 3.0           | -             | 7.57          | 3.43          |               |               |               |               |                |
| 5   | 0.89 | 8.03 | 1.33          | 0.37          | 0.32          | 2.8           | -             | 7.21          | 3.51          |               |               |               |               |                |
| 6   | 0.95 | 8.59 | 1.15          | 0.23          |               | 2.8           | -             | 7.04          | 3.51          |               |               |               |               |                |
| 7   | 0.96 | 8.76 | 1.14          | 0.26          | 0.22          | 2.8           | -             | 7.53          | 3.47          |               |               |               |               |                |
| 8   | 1.43 | 8.07 | 1.23          | 0.25          | 0.30          | 3.0           | -             | 7.74          | 3.43          |               |               |               |               |                |
| 9   | 0.20 | 10.47| 0.30          | 0.04          |               |               |               |               |               |               |               |               |               |                |
| 10  | 1.36 | 10.41| 0.31          | 0.23          |               |               |               |               |               |               |               |               |               |                |
| 11  | 1.57 | 10.59| 0.09          | 0.08          |               |               |               |               |               |               |               |               |               |                |
| 12  | 1.21 | 9.31 | 0.26          | 0.13          | 0.00          | 8.13          | -0.12         | 3.51          |               |               |               |               |               |                |
| 13  | 2.00 | 11.34| 0.33          | 0.16          |               | 9.94          | -0.77         | 3.51          |               |               |               |               |               |                |
| 14  | 1.90 | 11.24| 0.57          | 0.04          |               |               |               |               |               |               |               |               |               |                |
| 15  | 0.93 | 7.86 | 1.30          | 0.30          | 0.34          | 12.43         | 1.73          | 4.57          |               |               |               |               |               |                |
| 16  | 1.18 | 10.12| 0.25          | 0.11          |               | 9.36          | 0.49          | -0.76         | 0.09          |               |               |               |               |                |
| 17  | 1.43 | 9.91 | 0.34          | 0.02          |               | 10.90         | 0.64          | 0.39          | -0.13         |               |               |               |               |                |
| 18  | 1.82 | 12.65| 0.40          | 0.27          |               | 13.96         | -0.16         | 0.31          | 3.51          |               |               |               |               |                |
| 19  | 0.20 | 7.98 | 1.29          | 0.30          | 0.34          | 13.67         | 1.46          | 5.69          |               |               |               |               |               |                |
| 20  | 0.20 | 8.93 | 1.31          | 0.29          | 0.31          | 14.01         | 2.16          | 5.08          |               |               |               |               |               |                |
| 21  | 0.60 | 10.33| 1.29          | 0.28          |               |               |               |               |               |               |               |               |               |                |
| 22  | 0.36 | 12.45| 0.20          | 0.02          |               |               |               |               |               |               |               |               |               |                |
| 23  | 1.04 | 10.59| 0.26          | 0.20          |               |               |               |               |               |               |               |               |               |                |
| 24  | 1.04 | 10.50| 0.08          | 0.06          |               |               |               |               |               |               |               |               |               |                |
| 25  | 1.41 | 10.62| 0.33          | 0.74          |               |               |               |               |               |               |               |               |               |                |
| 26  | 1.50 | 10.68| 0.58          | 0.47          |               |               |               |               |               |               |               |               |               |                |
| 27  | 2.04 | 11.07| 0.42          | 0.36          |               |               |               |               |               |               |               |               |               |                |
| 28  | 1.09 | 12.00| 0.37          | 0.64          |               |               |               |               |               |               |               |               |               |                |
| 29  | 1.82 | 9.99 | 0.17          | 0.17          |               |               |               |               |               |               |               |               |               |                |
| 30  | 1.54 | 10.83| 0.12          | 0.15          |               |               |               |               |               |               |               |               |               |                |
| 31  | 1.00 | 8.27 | 1.14          | 0.26          | 0.29          |               |               |               |               |               |               |               |               |                |

*Johnson (1966) $V-K_0$ assumed.
Doradus Wolf-Rayet stars have been determined from published V magnitudes and an assumed bolometric correction to the V magnitude, $BC_V$, of -3.5 (HTR). All luminosities derived in this way are greater than the mean galactic Wolf-Rayet star luminosity (Conti 1976). This observation was first made by Westerlund and Smith (1964) from their absolute visual magnitude data and is not related to our choice of bolometric correction. The authors have suggested that the Doradus Wolf-Rayet stars are extremely young objects and as such they have not yet lost enough mass for their luminosities to have decreased to the normal galactic value. The effective temperatures of Wolf-Rayet stars cannot be estimated from the present data so, once again, for the purpose of including them in Figure 2 an approximate value of $\log T_e = 4.6$ has been adopted (Conti 1976). Any systematic errors in the bolometric magnitudes and effective temperatures of these Doradus Wolf-Rayet stars will be insufficient to affect the following discussion. For the other blue and yellow stars for which spectral types are available the bolometric corrections and effective temperatures appropriate to those spectral types have been taken from the calibration of Johnson (1966).

For the red stars, the (J-K)$_o$ colour has been used to derive the effective temperatures and bolometric corrections to the K magnitude, $BC_K$, from the calibrations of Lee (1970). Columns (11) to (14) of Table 3 contain the derived values.

(b) The Log L vs Log $T_e$ Diagram

The bolometric luminosities and effective temperatures from Table 3 are plotted in Figure 2, with the Wolf-Rayet stars plotted under the assumptions discussed above. Regions corresponding to the most probable domains of the galactic WN stars are shaded (Conti 1976). The heavy dashed line represents the completeness limit of the 2 µm survey of HTR, assuming
FIG. 2 - $M_{\text{BOL}}$ vs log $T_e$ diagram for the 30 Doradus region.

The Wolf-Rayet stars are plotted at the assumed log $T_e$ of 4.6.

The domains of galactic WN stars are shaded (Conti 1976).

The heavy dashed line represents the completeness limit of the 2 µm survey (HTR). Evolutionary tracks with (solid lines) and without (broken lines) mass loss are shown (Chiosi et al.).
the intrinsic colours of Johnson (1966) for normal supergiants with no
intrinsic deviations from a typical visual extinction of 1 mag. Although this
flux does not necessarily apply to the 1.5-micron band. It shows that
the lack of lower luminosity. High temperature objects in a process
result

-14
-13
-12
-11
-10
-9
-8
-7
-6
-5

MBOL

4.8
4.5
4.4
4.2
4.0
3.8
3.6
3.4

Log Te

R136

100 M_o

WN7

40 M_o

WN

20 M_o
the intrinsic colours of Johnson (1966) for normal supergiants with no infrared excesses and a typical visual extinction of 1 mag. Although this limit does not necessarily apply to the Wolf-Rayet stars, it shows that the lack of lower luminosity, high temperature objects is a probable result of the selection method employed.

Clearly a large discrepancy in luminosity exists between the brightest blue and red stars in Figure 2. As the effects of mass loss on the theoretical evolution of massive stars have been found to be significant (e.g., de Loore 1979), it is of interest to compare such evolutionary tracks with the 30 Doradus stars. Evolutionary tracks for models with initial masses of 20, 40, and 100 M\(_\odot\) (Chiosi, Nasi and Sreenivasan 1978) are shown in Figure 2 for the cases of no mass loss (broken lines) and high mass loss (solid lines). In both cases the post-main sequence evolution across the diagram occurs at approximately constant luminosity since for both cases temperature independent electron scattering is the dominant opacity source in the regions of energy production. Thus from an inspection of Figure 2 we can immediately reject the possibility that the hot stars evolve directly towards the lower luminosity cool stars as a result of mass loss.

Similarly, there is no theoretically plausible way for the Wolf-Rayet stars and the M supergiants to be end products of the same star formation event. This view is supported by empirical evidence from the Galaxy where M supergiants are only found in associations with ages \(\geq 10^7\) yr (Schild 1970). In these associations the main sequence turn-up occurs at B spectral types. The two stellar populations in the 30 Doradus region must, therefore, have formed in separate star formation events.
A knowledge of the age and evolutionary status of each population is required to probe the star formation history of the region. If the 30 Doradus Wolf-Rayet stars are single objects they lie approximately in the region of 100 M☉ stars, implying ages of \( \lesssim 3 \times 10^6 \) yr (HTR). If they are binary systems, interaction between the components may require this estimate to be increased slightly.

Two possibilities exist for the evolutionary status of the red supergiants, although in both cases the red supergiants are significantly older than the Wolf-Rayet stars. The red supergiants may be either high mass stars (\( M/M_\odot \gtrsim 10 \)) in the red supergiant region for the first time, having non-degenerate carbon-burning cores (e.g., Lamb, Iben and Howard 1976; LIH), or they may be intermediate mass stars (\( 3 \lesssim M/M_\odot \lesssim 9 \)) on the second giant branch with electron-degenerate carbon-oxygen cores and both hydrogen and helium-burning shells. Such stars attain exceptionally high luminosity for their mass before carbon detonation in the degenerate core causes a supernova explosion.

Evolutionary tracks for all stars of intermediate mass become indistinguishable in temperature on the second giant branch with the luminosity being related to the core mass simply by

\[
\frac{L}{L_\odot} = 59250 \frac{M}{M_\odot} - 30950
\]

(Paczynski 1970). Evolution proceeds in equal luminosity increments in equal times, resulting in an evenly populated, narrow giant branch (Wood 1974). The sudden onset of carbon detonation when the degenerate core mass reaches the Chandrasekhar limit (-1.4 M☉) results in a sharp cut-off at the top of the giant branch. The theoretical cut-off luminosity, derived from the Paczynski relation with a core mass of 1.4 M☉, is \( M_{\text{bol}} = -7.0 \) mag.
These two possibilities require examination. If the Doradus M supergiants are high mass objects, and if mass loss has not affected their evolution, they have masses of $-15\ M_\odot$, corresponding to ages of $1.2 \times 10^7\ yr$ (LIH). If mass loss has modified their evolution, the $20\ M_\odot$ track including mass loss in Figure 2 may be more appropriate. The most redward point on this track corresponds to an age of $-9 \times 10^6\ yr$ with a remaining stellar mass of only $8\ M_\odot$ (Chiosi, Nasi and Sreenivasan 1978). A search for the blue helium-burning supergiants associated with such core carbon-burning red supergiants was made in order to test the high mass hypothesis. The number of blue supergiants found in the 30 Doradus region is not inconsistent with predictions based on the high mass hypothesis, however the uncertainties involved prevent us drawing any more positive conclusions. If the Doradus M supergiants are high mass stars a significant mass range (with masses between $-12$ and $18\ M_\odot$) must exist among them in order to produce the observed luminosity range of $\geq 1\ mag$ in $M_{BOL}$.

If the Doradus M supergiants are intermediate mass stars the stellar mass cannot be uniquely identified from their luminosity. In this alternative, masses at the high mass end of the intermediate mass range (i.e., 7-9 $M_\odot$), with corresponding ages of $2-5 \times 10^7\ yr$ (Becker, Iben and Tuggle 1977), are suggested from the requirement that these stars terminate their evolution as supernovae, rather than by planetary nebula ejection (Tuchman, Sack, and Barkat 1978), and from the lack of carbon stars on the Doradus giant branch, despite the fact that intermediate mass stars in this evolutionary stage experience helium shell flashes (Iben 1977).

The observed giant branch morphology is consistent with theoretical predictions for intermediate mass stars, however, the observed upper
luminosity limit at $M_{\text{BOL}} = -7.8$ mag disagrees with the theoretical cut-off value of $M_{\text{BOL}} = -7.0$ mag. Consideration of the photometric errors for individual stars and of the uncertainties in reddening and bolometric corrections leads to a probable uncertainty in the observed luminosity cut-off of 0.2 mag. The difference between the theoretical and observed values is therefore significant.

This higher observed luminosity cannot be reconciled with uncertainties in the theoretical luminosity-core mass relation as several workers (cf. Fig. 8 of Becker and Iben 1980) have obtained essentially identical relations. If the Doradus M supergiants have intermediate masses, we are forced to require that their degenerate core mass exceeds the Chandrasekhar limit by $-0.8 M_\odot$. This fact makes the intermediate mass interpretation difficult to accept, however core rotation is a possible mechanism for achieving this situation. No detailed calculations of rotating stellar evolution through to carbon detonation have been made to date, but crude calculations (Sackmann and Weidemann 1972) suggest that luminosities of the required order may be achieved.

We are unable to unequivocally determine the evolutionary status of the 30 Doradus M supergiants at this stage, however there is currently some cause to favour the high mass hypothesis. The present data confirm the earlier conclusion of HTR that at least two major star formation events have occurred in the 30 Doradus region in the last $-5 \times 10^7$ yr or less and allow better estimates of the epochs of these events to be made. The first event occurred between $-1 \times 10^7$ and $-3 \times 10^7$ yr ago, depending on whether the Doradus M supergiants are high or intermediate mass stars, respectively, while the second occurred $\leq 3 \times 10^6$ yr ago. If star
formation in the region had been continuous during this interval we would now expect to see red supergiants with luminosities covering the full range up to the maximum possible in the LMC ($M_{\text{BOL}} = -9.5$ mag; Humphreys 1979a, Glass 1979). This is not observed; as Figure 2 shows, the observed giant branch in the Doradus region extends only to $M_{\text{BOL}} = -7.8$. HTR identified the more recent event with the formation of the nebula.

The supernova rate for the older population can easily be derived under the assumption that the Doradus M supergiants are intermediate mass stars. From the rate of evolution of such stars up the second giant branch of $0.77$ mag/$10^6$ yr (Iben (1976) as quoted by LIH), the eleven stars with $M_{\text{BOL}} = -6.5$ to $-8.0$ mag represent a time span of $-2 \times 10^6$ yr, leading to a supernova rate for the older population of $-5$ S.N. per $10^6$ yr. If the Doradus M supergiants are actually high mass stars, the supernova rate will exceed this value since their evolution will be more rapid. Using a lifetime for the radio detection of a supernova remnant in the LMC of $-10^5$ yr, the probability of detecting a supernova remnant in this region at present is $\geq 0.5$. The non-thermal radio source N157B is a young supernova remnant (Le Marne 1968; Long and Helfand 1979) and lies within the survey region (Fig. 1).

IV. THE STELLAR POPULATIONS

(a) The Blue Population

(i) Mass Loss Rates

Infrared photometry has been used in several studies to estimate the mass loss rates of early-type stars (e.g., Barlow and Cohen 1977; Hyland 1979; Barlow, Smith and Willis 1980). Hyland showed that the free-free emission from mass loss outflows can be detected as excess radiation to wavelengths as short as 2 $\mu$m. This possibility greatly extends the
power of the infrared free-free flux method of mass loss determination since routine measurements can be made to as faint as K - 15 mag using present infrared instrumentation. The more rigorously calibrated determinations requiring 10 μm fluxes are limited to sources brighter than -6 mag at 10 μm. The short wavelength infrared method is consequently the only infrared means by which mass loss rates can be obtained for the distant Doradus OB supergiants.

Following Hyland (1979), we estimate the excess reddening in (J-K) caused by free-free emission from a mass loss outflow (E_f(J-K) in Hyland's notation) from a plot of (B-V) vs (J-K) for the blue stars in this study with published optical photometry (Fig. 3). Open circles in Figure 3 represent stars lacking optical photometry but plotted at the (B-V)_0 colour appropriate to their spectral type (Johnson 1966). Optical photometry was not available for the Wolf-Rayet stars Dor IR 14 and Dor IR 30 which have (J-K)_0 positions marked by arrows.

Clearly the Wolf-Rayet stars Dor IR 15, 21, 27 and 30 have significant (J-K)_0 excesses; a result which is not altered by uncertainties in reddening corrections. Dor IR 14 (WN6) is also likely to have a significant excess, as does the B0.5 star Dor IR 34. No free-free excess is found for the Wolf-Rayet star Dor IR 16 whose colours have previously been shown to be uncertain due to significant background emission in its vicinity. For Dor IR 5, it is apparent from Figure 3 that the reddening correction has been underestimated as the colours of this star do not correspond to the intrinsic colours appropriate to its spectral type. Dereddening Dor IR 5 further to the (B-V)_0 colour of a B9I star places it on the mean galactic line with no infrared excess. On the other hand, the reddening corrections for Dor IR 19 and 20 may have been slightly overestimated. Their positions
FIG. 3 - $(B-V)_0$ vs $(J-K)_0$ diagram for the blue supergiants.

Filled circles use published optical photometry, open circles use $(B-V)_0$ colours appropriate to published spectral types.

The mean galactic supergiant line is taken from Johnson (1966). Arrows representing the reddening corresponding to an absorption at Hβ of 2.0 mag are shown for the adopted extinction law ($R=5$) and the normal galactic extinction law ($R=3.1$). Excess infrared radiation due to free-free emission from mass loss outflows is seen as a reddening in $(J-K)_0$. 
The measured intrinsic color (B-V) and (J-H) of the stars are plotted on the diagram. The data points represent various types of stars, such as O, B, A, F, G, and K. The stars are plotted according to their intrinsic colors, with different symbols indicating different types of classification. The plot shows a trend where the color indices (B-V) and (J-H) decrease with increasing temperature, which is consistent with theoretical predictions for the evolution of stellar populations.
to the blue of the mean galactic line in (J-K) also suggest that the adopted R = 5 extinction law may not be appropriate for these two stars.

The measured excesses are tabulated in Table 4 along with the corresponding ratios of mass loss rate to terminal flow velocity, $\dot{M}/v_\infty$, obtained from the calibration of Hyland (1979). The $\dot{M}/v_\infty$ ratios obtained from Hyland's calibration for the Wolf-Rayet stars have been reduced by a factor of 4 in order to obtain agreement between the more accurate determinations of Barlow et al. and data from Hyland (1979) for the Carina Wolf-Rayet stars HD 93131 and HD 93162 which are common to both studies. Errors in the Wolf-Rayet star excesses are ±0.1 mag while the errors in determining individual $\dot{M}/v_\infty$ ratios are estimated to be ±0.3 dex.

The terminal flow velocity for Dor IR 15, the central object in the 30 Doradus cluster (R136 in Feast et al.), measured from P Cygni profiles of ultraviolet lines, is 3300 km sec$^{-1}$ (de Boer et al.). The mean flow velocity of 2000 km sec$^{-1}$ for galactic WN stars in the Barlow et al. sample has been adopted for the remaining Wolf-Rayet stars. An order of magnitude estimate of $10^3$ km sec$^{-1}$ was used for the terminal flow velocity of the OB stars. Individual mass loss rates are given in Table 4 and may be in error by up to ±0.8 dex.

Significant mass loss is seen in the B0.5 Ia star Dor IR 34 but is not seen in the other B0.5 supergiant Dor IR 17 or the A0 supergiant Dor IR 33. This is in line with current understanding of the types of stars experiencing mass loss. The plot of mass loss rate versus bolometric magnitude for all the Doradus stars with detectable mass loss (Fig. 4) shows some evidence for a correlation between these quantities. Such a correlation has been empirically shown to exist for galactic O stars (Barlow and Cohen 1977; Abbott et al. 1980) and was predicted theoretically for a radiation pressure driven outflow (Castor, Abbott and Klein...
Table 4

Mass Loss Rate Derivation

<table>
<thead>
<tr>
<th>Dor IR No.</th>
<th>SpT</th>
<th>$E_f$(J-K) (mag)</th>
<th>$\log_{10} \dot{M}/v_{\infty}$ (M$_\odot$ yr$^{-1}$/km sec$^{-1}$)</th>
<th>$\langle v_{\infty} \rangle$ (km sec$^{-1}$)</th>
<th>$\dot{M}$ (M$_\odot$ yr$^{-1}$)</th>
<th>$&lt;m_{10 \ \mu m}&gt;$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>B9I</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.1</td>
</tr>
<tr>
<td>14</td>
<td>WN6</td>
<td>0.3</td>
<td>-7.9</td>
<td>2000</td>
<td>$3 \times 10^{-5}$</td>
<td>9.6</td>
</tr>
<tr>
<td>15</td>
<td>O+WN</td>
<td>0.3</td>
<td>-7.9</td>
<td>3300</td>
<td>$4 \times 10^{-5}$</td>
<td>6.8</td>
</tr>
<tr>
<td>16</td>
<td>WN7+0:</td>
<td>(0.0)</td>
<td>-</td>
<td>2000</td>
<td>-</td>
<td>11.6</td>
</tr>
<tr>
<td>17</td>
<td>B0.5:</td>
<td>0.1</td>
<td>$&lt;-8.5$</td>
<td>1000</td>
<td>$&lt;3 \times 10^{-6}$</td>
<td>10.6</td>
</tr>
<tr>
<td>19</td>
<td>F7Ia</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.3</td>
</tr>
<tr>
<td>20</td>
<td>G5</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.1</td>
</tr>
<tr>
<td>21</td>
<td>WN5+</td>
<td>0.6</td>
<td>-7.4</td>
<td>2000</td>
<td>$8 \times 10^{-5}$</td>
<td>9.8</td>
</tr>
<tr>
<td>27</td>
<td>WN7</td>
<td>0.3</td>
<td>-7.9</td>
<td>2000</td>
<td>$3 \times 10^{-5}$</td>
<td>9.0</td>
</tr>
<tr>
<td>30</td>
<td>WN7</td>
<td>0.7</td>
<td>-7.2</td>
<td>2000</td>
<td>$1 \times 10^{-4}$</td>
<td>8.7</td>
</tr>
<tr>
<td>33</td>
<td>AO:I:</td>
<td>0.1</td>
<td>$&lt;-8.5$</td>
<td>1000</td>
<td>$&lt;3 \times 10^{-6}$</td>
<td>9.4</td>
</tr>
<tr>
<td>34</td>
<td>B0.5Ia</td>
<td>0.3</td>
<td>-7.3</td>
<td>1000</td>
<td>$5 \times 10^{-5}$</td>
<td>9.5</td>
</tr>
</tbody>
</table>
Conti and Garmany (1980), however, have presented evidence that some O stars do not obey this type of relation. The O star data of Conti and Garmany and the galactic Wolf-Rayet star data of Barlow et al. are also plotted in Figure 4 for comparison. The $M_{\text{bol}}$ versus $\dot{M}$ relation of Abbott et al. (1980) is also shown. The Doradus data show agreement with the general correlation of mass loss rate with $M_{\text{bol}}$ found by the above authors, however the precision of the analysis is insufficient for us to comment further.

The comparison of galactic and 30 Doradus Wolf-Rayet star mass loss rates is also of interest. The mean mass loss rate for the 15 galactic WN stars in the Barlow et al. study using the 10 µm flux method is $3.2 \times 10^{-5} M_\odot \text{yr}^{-1}$. The mean mass loss rate found here for the five Doradus Wolf-Rayet stars Dor IR 14, 15, 21, 27 and 30 exceeds this galactic mean by only a factor of -2 even though the mean luminosity of the 30 Doradus Wolf-Rayet stars is -3 mag brighter than the mean luminosity of the Barlow et al. galactic stars. This result clearly demonstrates that the narrow range of Wolf-Rayet star mass loss rates found by Barlow et al. also extends to higher luminosities than they have considered. The different loci in the mass loss rate versus luminosity plane for the Wolf-Rayet stars and galactic O stars indicate that different mechanisms are responsible for the mass loss in these stars. Nevertheless, it appears that both mechanisms produce similar mass loss rates for luminosities in the range $-10 \geq M_{\text{bol}} \geq -13$, i.e., the range occupied by the 30 Doradus Wolf-Rayet stars. The predicted 10 µm fluxes in Table 4 vividly demonstrate the difficulties involved in attempting mass loss rate determinations for the Doradus OB supergiants by the 10 µm flux method.
FIG. 4 - Mass loss rate versus $M_{\text{bol}}$ diagram for the 30 Doradus Wolf-Rayet stars (filled circles), 30 Doradus OBA supergiants (filled triangles), galactic O stars from Conti and Garmany (1980) (open circles), and galactic WN stars from Barlow et al. (crosses). ABCC marks the relation of Abbott et al. (1980).
The consequences of these high mass loss rates on the evolution of the Doradus Wolf-Rayet stars and their interaction with the interstellar medium will be significant. The Doradus Wolf-Rayet stars cannot maintain their high mass loss rates over long time scales without severely altering their masses. The mass loss rates can therefore be used to place even tighter limits on the present ages of the Doradus Wolf-Rayet stars. Assuming that they had initial masses of $-100 \, M_\odot$ and that they have maintained their current mass loss rates for a significant fraction of their lifetime (a reasonable assumption considering their luminosities), the ages of the Doradus Wolf-Rayet stars must be significantly less than $-10^6 \, \text{yr}$, since in that time many of them would have lost almost their entire mass. This result is in agreement with the suggestion of Westerlund and Smith (1964) that the Doradus Wolf-Rayet stars are extremely young objects. Consequently, the formation of the blue population in 30 Doradus must have taken place even more recently than earlier thought.

Blades and Meaburn (1980) have suggested stellar wind phenomena to explain broad interstellar absorption features observed in the optical spectrum of Dor IR 15 (R136).

(ii) \textit{2 \mu m CVF Spectrum of the Central Object}

The 2 \mu m CVF spectrum of R136 is shown in Figure 5. The object is extended on a scale of about 2 arcsec (Feast 1961) and is probably a very compact cluster of WN and O stars. The emission feature centered on 2.18 \mu m is a blend of He II lines between 2.17 \mu m and 2.19 \mu m from the Wolf-Rayet star component with a possible contribution of Brackett-$\gamma$ at 2.17 \mu m from uncancelled nebular emission or from the Wolf-Rayet component.
FIG. 5 - 2 µm CVF spectra of the 30 Doradus supergiants.

Dor IR 15, the central object in the 30 Doradus cluster, shows HêII emission around 2.18 µm from the Wolf-Rayet star component. The remaining stars are M supergiants showing CO absorption longward of 2.3 µm. The CO indices measured from these spectra ratio the continuum region (Region A) to the absorption region (Region B). The late-type supergiants are placed in order of increasing CO band strength.
There is no suggestion of CO absorption longward of 2.3 µm, indicating the absence of any significant late-type stellar component. A late-type component is not expected in an object of this age. The positive continuum slope, indicating that the infrared continuum colour in this object is redder than in the standard star, BS2015 (A6IV), is due to the presence of strong free-free emission from the mass low outflow around R136.

(b) The Red Population

Spectroscopic studies in the LMC (Humphreys 1979a) have failed to detect any strong differences between LMC and galactic M supergiants. Similar studies in the Small Magellanic Cloud (SMC) (Humphreys 1979b) have discovered differences in the spectral type distribution of late-type supergiants between the SMC and the Galaxy which may be explicable in terms of metal deficiency in the SMC stars. Such deficiencies, if they exist in the LMC supergiants, may be more apparent in the infrared properties of the M supergiants. In the following we compare our infrared photometry of 30 Doradus M supergiants with similar galactic data in order to investigate their infrared characteristics and to identify any photometric differences existing between the M supergiants in these two galaxies.

(i) Observed Two-Colour Diagram

The Doradus M supergiants lie in the region of spectroscopic luminosity class Ib galactic stars (Lee 1970) in the (J-H) vs (H-K) diagram (Fig. 6). Data for the brightest variable LMC M supergiants (Glass 1979) and for twelve stars which form part of the halo of M supergiants around h and Χ Persei and for which H magnitudes were available (Lee 1970) are also plotted. No published H magnitudes are available for the M supergiants within the h and Χ Persei cluster.
FIG. 6 - Two colour diagram for the 30 Doradus M supergiants.

Data for the brightest LMC late-type supergiants (Glass 1979) and for M supergiants in the vicinity of the galactic open clusters h and X Persei (Lee 1970) are also shown. The mean galactic supergiant and giant lines are from Lee (1970) and Frogel et al. (1978). The arrow represents the reddening corresponding to an absorption at H8 of 2.0 mag.
A clear colour separation of -0.13 mag in J-H results between the LMC and the more normal stars in the Glass amplitudes. This separation is commensurate in the direction of interstellar reddening. LMC Glass (1979) three stars are indicated in the figure. Right ascension variability in the Glass stars appears to be high over areas of 0.05 square degrees. Most of these stars are indicated in the figure. Figure 5 shows the other Glass variables.
A clear colour separation of -0.15 mag in J-H exists between the Doradus stars and the more luminous LMC stars in the Glass sample. This separation is perpendicular to the direction of interstellar reddening and so cannot be due to uncertainties in the applied reddening corrections. The separation is also unlikely to be due to abundance differences since both samples were taken from the same galaxy. A similar separation between the mean lines of luminosity class Ib and Ia galactic M supergiants in the (J-H)$_o$ vs (H-K)$_o$ plane has been known for some time (Lee 1970). The cause of this separation is clearly related to the luminosity differences between these stars.

The association of position in the (J-H)$_o$ vs (H-K)$_o$ plane with luminosity suggests the existence of a correlation between these quantities which may have applications in distance determinations. To test for this correlation we define the reddening independent variable, (J-H)$_{1.00'}$, to be the J-H colour of an M supergiant after it has been dereddened along the normal galactic reddening line to J-K = 1.00 mag. This colour defines the location of a star roughly perpendicular to the reddening line in the J-H vs H-K plane. In Figure 7 bolometric magnitude is plotted versus (J-H)$_{1.00}$ for the late-type LMC supergiants in 30 Doradus and in the Glass sample. The considerable scatter in Figure 7, which is probably due to variability in the Glass stars, degrades any strong correlation. The situation would be significantly improved if the three stars near ((J-H)$_{1.00'}$, $M_{\text{BOL}}$) = (0.77, -6.5) were omitted. At least two of these stars are intermediate mass stars with $M/M_\odot$ ~ 4.5 (Wood 1980), whereas the other Glass variables appear to be high mass stars. Figure 7 cannot be meaningfully used to determine bolometric magnitudes of individual M supergiants, however it may be possible to determine the mean bolometric magnitude of a population of M supergiants by this method.
FIG. 7 - $M_{bol}$ versus $(J-H)_{1.00}$ for the LMC late-type supergiants.

$(J-H)_{1.00}$ measures the position of a star in the $(J-H)_o$ vs $(H-K)_o$ plane perpendicular to the normal reddening lines (see text).
if sufficient data are available for the mean relation to be defined. Due to the nature of the correlation, it is unlikely that mean distance moduli could be determined to better than half a magnitude in this way.

Despite their apparently normal positions in Figure 6, the locations of the LMC stars in the (J-H)_o vs (H-K)_o plane are in conflict with expectations based on their luminosities and the positions of the h and X Persei stars of the same luminosity. Adopting a mean distance modulus of 11.9 for the h and X Persei stars (Wildey 1964) and applying reddening corrections such that (B-V)_o is set equal to 1.6 (Johnson and Mendoza 1966), it can easily be shown that the h and X Persei supergiants in this study have a similar absolute K magnitude distribution to the 30 Doradus M supergiants (Fig. 8). On luminosity grounds alone then the h and X Persei and 30 Doradus stars should both lie at the same position (i.e., have similar (J-H)_1.00 colours) in the (J-H)_o vs (H-K)_o plane. Similarly, stars in the Glass sample which are more luminous than the h and X Persei stars are expected to lie at bluer (J-H)_1.00 colours than the h and X Persei stars. Inspection of Figure 6 shows that neither of these expectations is realised. Since the h and X Persei stars do not occupy anomalous positions in the (J-H)_o vs (H-K)_o diagram, we conclude that it is the LMC supergiants which occupy anomalous positions in the (J-H)_o vs (H-K)_o plane (i.e., have redder (J-H)_1.00 colours) relative to galactic M supergiants of the same luminosities. A metal abundance difference between the two galaxies is a likely explanation.

(ii) Theoretical Interpretation

In order to gain a physical understanding of the colour separation of stars of different luminosity and of the anomalous positions of LMC supergiants relative to galactic supergiants in the (J-H)_o vs (H-K)_o plane, theoretical broad band infrared colours have been computed from
FIG. 8 - Histograms of the distribution of absolute $K$ magnitude for (a) the brightest LMC late-type supergiants, (b) 30 Doradus M supergiants and (c) M supergiants in the vicinity of the galactic clusters h and X Persei which are plotted in Fig. 6.
a grid of supergiant model atmospheres. Details of these calculations are
given in Appendix II, with only a brief outline being presented here.

The models were obtained by interpolation and extrapolation on the
grid of model atmospheres of Bell, Eriksson et al. (1976), supplemented
with six similar log g = 0.0 models kindly provided by B. Gustafsson.
Flux distributions through the J, H, and K bands were computed using the
model atmosphere program ATLAS5 (Kurucz 1970). CO, TiO and atomic line
opacities were not included in the flux calculations, however the infrared
opacity of the CN molecule was included through the tabulated straight
mean opacities of Johnson, Marenin and Price (1972). Justifications for
these choices are given in Appendix III. The omissions will introduce
significant errors (~0.05 mag) in the absolute values of the resulting
colours, however the differences between luminosity class Ia and Ib
colours should not be seriously affected.

The computed fluxes have been convolved with the M.S.O. filter
transmissions, allowing for a detector response function proportional
to wavelength and using the Kitt Peak summer sky transmission adopted
by Manduca and Bell (1979) to approximate atmospheric conditions at
Siding Spring Observatory. The theoretical infrared colours produced
have been zero-pointed by comparison with α Ori and α Boo and the
resulting colours transformed to the Johnson system using the same J band
transformation as applied to the observed colours. These computed
colours are not expected to be of high absolute accuracy, however, as
mentioned above, they should be sufficient to demonstrate the existence
of any colour differences due to the CN opacity between different models.

The computed colours for models in the expected range of effective
temperature and surface gravity with abundances of solar and all metals
deficient by factors of 3 and 10 are shown in Figure 9(a) - (c). For each abundance, different symbols represent different surface gravities, with surface gravity decreasing to redder \((H-K)_0\) in each case. Solid lines join points of the same gravity but different temperature, with temperature decreasing to redder \((J-H)_0\) in each case.

The strong sensitivity of \((J-H)_0\) to temperature seen in Figure 9 is due to the predominance of the \(H^-\) ion opacity in these stars. Opacity in the J pass band is due to the bound-free component of \(H^-\), while in the H pass band it is due to the free-free component which strengthens towards longer wavelengths. The location of the \(H^-\) ion opacity minimum in the H pass band allows \((J-H)_0\) to measure a temperature gradient between two depths in the atmosphere. As the stellar effective temperature decreases the degree of association of the \(H^-\) ion increases, increasing the importance of the bound-free component relative to the free-free component. The greater opacity contrast between J and H allows a greater contrast in the depths of continuum formation in these bands and hence an increase in the measured temperature difference.

The separation in colour of stars of different gravity in Figure 9 is found to be a consequence of the positive luminosity dependence of the CN opacity in M supergiants. The predicted changes in colour are most easily explained by a reduction in flux through the H pass band at lower gravities where CN absorption is strongest. This simultaneously makes J-H bluer and H-K redder. If the CN opacity is omitted from the calculations the colours of all models move at constant \((J-K)_0\) to the approximate position of the \(\log g = 2.25\) model of the same effective temperature, thus demonstrating that CN absorption is responsible for all of the predicted colour separation.
FIG. 9 - Theoretical colours for giant and supergiant models in the log $T_\text{e}$ - log g domain of the late-type 30 Doradus supergiants for (a) solar abundance, (b) all metals deficient by 0.5 dex, and (c) all metals deficient by 1.0 dex. The shaded regions indicate the domain of stars on the giant branch of the galactic globular cluster, M71 (Frogel et al. 1979).
The observed separation of both the galactic Ib and Ia supergiants and of the 30 Doradus and the more luminous LMC supergiants in Figure 6 can now be interpreted as due to the effects of increasing CN absorption in the lower surface gravity models. Lower gravity models, corresponding to higher luminosity stars (if the stellar mass remains constant), are shifted to bluer \((J-H)_0\) and redder \((H-K)_0\) colours (i.e., to bluer \((J-H)_{1.00}\) colours). The magnitude of this separation with surface gravity is dependent on metal abundance with the present approximate calculations predicting the separation to be non-existent at metal deficiencies of a factor of 10 (Fig. 9(c)). On the basis of these calculations, the existence of a detectable colour separation between LMC supergiants of different luminosities indicates that the LMC supergiants cannot be deficient by more than about a factor of 3 relative to solar abundance. The effects of blanketing by infrared lines of CN on late-type stellar atmospheres have been discussed previously (Gustafsson et al. 1975, Bell, Gustafsson et al. 1976), however the observed separation in colour of M supergiants in the \((J-H)_0\) vs \((H-K)_0\) plane has not previously been explicitly associated with the CN molecular opacity.

The anomalous colours of the LMC supergiants in the \((J-H)_0\) vs \((H-K)_0\) plane can be interpreted in terms of the effects of lower CN absorption on the colours of metal deficient stars. The lower CN number densities in deficient stars reduce the CN band strengths which in turn causes the colours of deficient stars to mimic those of lower luminosity (higher gravity) stars of solar composition. This effectively shifts the colours of deficient stars to redder \((J-H)_0\) and bluer \((H-K)_0\) colours (i.e., to redder \((J-H)_{1.00}\) colours). The considerable colour differences between LMC and galactic stars of the same luminosity indicates that the LMC stars must be deficient in metals by a significant amount. This result, in combination
with the above result that the LMC M supergiant abundance deficiency
cannot exceed about a factor of three, indicates an abundance deficiency
for the LMC late-type supergiants which is not inconsistent with the
presently accepted mean deficiency of a factor of 2-3 for the LMC.

Further theoretical discussions of the broad band infrared colours
of M supergiants must await the computation of accurate colours from
detailed model atmosphere flux distributions. Investigations of the
effects of sphericity and deviations from local thermodynamic equilibrium
(LTE), which have been ignored in the present simple calculations, on the
colours of M supergiants will be of importance since at present it is
not known to what extent the atmospheres of late-type giants and super-
giants can be compared.

(iii) \((J-K)_o\) as a Temperature Indicator

The computed colours in Figure 9 show a remarkable constancy of \((J-K)_o\)
with changes in surface gravity over a range of 3 dex and of abundance
from solar to all metals deficient by a factor of 10, even when the effects
of CN absorption are included. (Lines of constant \((J-K)_o\) in Figure 9
cross the diagrams with slope of -1 at 45° to the coordinate axes). The
\((J-K)_o\) colour is therefore seen to be a valuable indicator of effective
temperature in late-type giant and supergiant stars. In Figure 10 we
indicate by bars the maximum and minimum \((J-K)_o\) colour attained by all
models in Figure 9 for each value of effective temperature. The maximum
range in effective temperature for a given \((J-K)_o\) colour is less than 120K.
The synthetic colours computed here are not of sufficient accuracy for the
plot of \((J-K)_o\) versus effective temperature to be taken as a theoretical
calibration of the index. An empirical calibration based on accurate
stellar effective temperatures such as those of Ridgway et al. (1980) is
required to place this relation on a firm footing.
FIG. 10 - Theoretical $(J-K)_0$ colour versus model effective temperature relation for data in Fig. 9. The small range of $(J-K)_0$ colour found for each effective temperature indicates the worth of $(J-K)_0$ as a temperature indicator in late-type stars.
(iv) Application to Globular Cluster Stars

Since some stars at the tip of globular cluster giant branches lie in the same log $T_e$ - log $g$ domain as the 30 Doradus supergiants, the CN opacity may also influence their infrared colours. The effect of CN absorption is expected to be most apparent in the highest luminosity giant stars in relatively metal rich clusters. These stars fall at the extreme tip of the giant branch. Previous synthetic infrared colours of globular cluster giant stars (Cohen, Frogel and Persson 1978) have matched the observed giant branch star colours without the inclusion of CN opacity, however these colours were generally compared with higher gravity, extremely metal deficient stars. Both these properties act to decrease the importance of CN absorption.

Two stars at the top of the giant branch of the metal rich galactic globular cluster M71 (Frogel, Persson and Cohen 1979) define a turn over of the giant branch in the $(J-H)_0$ vs $(H-K)_0$ plane (Fig. 9, shaded region). It is possible that CN opacity is important in determining the infrared colours of these stars. Carbon and nitrogen abundance anomalies in such stars may be apparent in the $(J-H)_0$ vs $(H-K)_0$ plane.

(v) CO Absorption Band Strengths

CO indices for the M supergiants are plotted in Figure 11 against $(J-K)_0$ which, as seen above, can be taken as indicating effective temperature. The mean galactic field giant line (Frogel et al. 1978) and dereddened data for galactic M supergiants (transformed from Baldwin et al. using $COF = 1.75 COB$) are also shown. The domain of stars in the galactic globular cluster M71 (Frogel et al.) is shaded.
FIG. 11 - CO index vs (J-K)_0 diagram for the 30 Doradus M supergiants (filled circles). The galactic field giant line (Frogel et al., 1978) and the domain of giant branch stars from M71 (Frogel et al.) are also shown. Published data for galactic M supergiants (open triangles) have been transformed from Baldwin et al. The arrow represents the reddening corresponding to an absorption at H8 of 2.0 mag.
Galactic supergiants are known to lie above the galactic red giant line in Figure 11. The origin of the larger O2 band strengths in galactic supergiant stars is not clear. Determining the attributes it to the effects of the higher microvirulence in supergiant stars on calculated density decrease and the iron abundance ratio. In the solar neighborhood, the O2 bands are formed in the surface layers of the stars, the iron abundance is insufficient to produce the emission intensity. The evidence of the high strengths of the FeO band is confirmed by the association of the supergiant's surface temperature with the near-infrared spectral type. A good fit is obtained with the solar metallicity of the galactic supergiants. The effects of abundance variations on the O2 band strengths in supergiants with lower than solar metallicity in the Magellanic Cloud supergiants...
Galactic supergiants are known to lie above the galactic field giant line in Figure 11. The origin of the larger CO band strengths in galactic supergiant stars is not clear. Baldwin et al. attribute it to the effects of the higher microturbulence in supergiant stars on saturated molecular lines. However, Hyland (1974) points out that the band strength is also dependent on the H⁻ ion number density through its continuum opacity. At the lower electron pressures in supergiant atmospheres the H⁻ ion number density decreases and the lower continuum opacity and associated higher continuum flux also act to increase the measured band strength. Since carbon and oxygen are almost fully associated in these stars, the CO bands are formed in the outer layers of the atmosphere. The effects of sphericity and non-LTE on the observed CO band strengths in M supergiants may therefore be significant (Spinrad et al. 1970).

The dependence of band strength on abundance is complicated by the fact that at these temperatures electrons are supplied predominantly by the ionization of metals and the positive effect of lower electron pressure in metal deficient stars through the H⁻ ion opacity opposes the negative effect of decreasing CO number density. The exact nature of the abundance dependence is therefore difficult to predict.

The Doradus supergiants form a well-defined sequence in Figure 11, parallel to and above the mean galactic giant line. The scarcity of data for galactic supergiants makes it difficult to define a mean galactic supergiant line in the (CO)₀ vs (J-K)₀ plane. Nevertheless, it is clear that at a given (J-K)₀, i.e., effective temperature, the galactic supergiants have larger CO indices than the Doradus supergiants. The effects of abundance variations on the CO band strengths in supergiants still need to be investigated, however, the present results are consistent with lower than solar metallicity in the Magellanic Cloud supergiants.
(vi) $H_2O$ Absorption in the 30 Doradus Supergiants

As mentioned earlier, the 2 µm spectrum of the star Dor IR 6 shows significant water vapour absorption shortward of 2.1 µm (cf. Hyland 1974a). This object is thus unusual among M supergiants, which generally show no $H_2O$ absorption (Baldwin et al.). It is probably similar to the peculiar late-type supergiants VY CMa, VX Sgr and NML Cyg, which are also known to exhibit water vapour absorption (Hyland 1974b).

We note that Dor IR 6 is the coolest of the Doradus supergiants studied (according to its $(J-K)_0$ colour) and suggest that the presence of $H_2O$ absorption may be related to its low effective temperature (-3000K). Its colours and the presence of $H_2O$ absorption are reminiscent of those of the SMC supergiant HV11417 which has recently been discussed in the literature (Elias, Frogel and Humphreys 1980).

Crude $H_2O$ indices have been measured for each of the ten Doradus late-type supergiants from their 2 µm spectra by extrapolating the infrared continuum slope between 2.15 µm and 2.25 µm to 2.075 µm and estimating the mean absorption below this continuum between 2.05 µm and 2.10 µm by eye. These differ from the narrow band indices of Frogel et al. (1978) in being a direct measurement of the band depth at -2.075 µm. The resulting $H_2O$ indices in magnitudes are plotted in Fig. 12 against $(J-K)_0$. It can be seen that for $(J-K)_0 \lesssim 1.3$ there is no convincing evidence for $H_2O$ absorption in the Doradus supergiants. Above $(J-K)_0 \sim 1.3$, $H_2O$ absorption becomes apparent, however, Dor IR 6, with an $H_2O$ index of 0.062, is the only star in which $H_2O$ absorption is undoubtedly present. Effective temperatures based on $(J-K)_0$ for supergiants with $(J-K)_0 > 1.3$ may thus be uncertain due to the possible presence of $H_2O$ blanketing in these stars. We note that the CN and $H_2O$ infrared absorption bands were
FIG. 12 - H$_2$O index vs (J-K)$_0$ diagram for the 30 Doradus M supergiants. The procedure used to measure H$_2$O indices from the 2 µm spectra (Fig. 5) is explained in the text.
initially confused (Wing and Spinrad 1970). As with CN then (see §IV(b) ii), the effect of H$_2$O absorption on (J-K)$_0$ may be quite small.

(vii) **Summary**

Differences in the broad band infrared colours and CO band strengths of galactic and LMC M supergiants have been found. Spectroscopic studies in the literature had not detected differences between the M supergiants in these two galaxies. The anomalous broad band infrared colours can be interpreted as due to metal deficiency in the LMC supergiants acting through the weaker infrared CN absorption bands. The weaker CO bands strengths in the 30 Doradus M supergiants are consistent with such abundance deficiencies. Water vapour absorption has been detected in the 2 µm spectrum of the M supergiant Dor IR 6.

V. IMPLICATIONS FOR STAR FORMATION IN THE REGION

The 30 Doradus complex lies in the midst of a much larger young star cloud which is known to contain many red supergiants (Westerlund 1964). Large-scale star formation of this sort took place throughout several regions of the LMC in one major burst beginning $\sim 10^7$ yr ago (Ardeberg 1976). In the foregoing, the 30 Doradus M supergiants were shown to have ages of this order and therefore most likely formed as part of this larger star formation event. The blue supergiant population and the 30 Doradus Nebula itself, formed in a more recent event and in the same region of space as the red population.

This star formation history is shared with the Magellanic Cloud blue globular clusters which are known, from the similarities of their colour-magnitude diagrams with those of nearby field regions (Robertson 1974 and references therein), to have formed as part of larger star formation events.
Age differences of the order of those existing between the blue and red Doradus population (-1 \times 10^7 \text{ yr}) could not now be distinguished between the cluster and field colour-magnitude diagrams of blue globular clusters whose ages lie in the range $10^7 - 10^8 \text{ yr}$. The prior condensation of massive stars throughout a larger volume of space may therefore be a common feature of all globular cluster star formation histories.

This star formation history can be compared with massive OB star formation in the Galaxy which is thought to proceed in a sequential manner at the edges of large molecular clouds. Shock fronts associated with either ionization fronts, supernovae or stellar winds from recently formed OB stars compress adjacent layers of the parent molecular cloud, causing gravitational instabilities which lead to further star formation.

Sequential formation due to ionization-induced shocks has been investigated theoretically by Elmegreen and Lada (1977). This method is likely to dominate over supernova-induced shocks after the initial population has formed (Lada, Blitz and Elmegreen 1978). Adopting -10^7 yr as the time between bursts of star formation in a similar application of the Elmegreen and Lada theory as presented by HTR, leads to a parent cloud density of 70 cm$^{-3}$ and a mean distance for the shocks to have travelled of -130 pc, corresponding to -8 arcmin at the distance of the LMC. The conclusions HTR reached by applying the Elmegreen and Lada theory to the 30 Doradus situation therefore remain unaltered: the distance estimate is of the order of the spatial extent of the older red population identified in the 30 Doradus region, and the derived cloud density is lower than observed in galactic molecular clouds, being more appropriate to a galactic HI cloud. The 30 Doradus region does not show any well defined temporal formation sequence as found in the subgroups of galactic OB associations (Blaauw 1964), and which have been used as evidence for
sequential formation in the Galaxy, and no mechanism is apparent in the
galactic star formation scenario for encouraging the formation of compact,
globular-like condensations. Sequential formation of OB stars as
encountered in the Galaxy is, therefore, difficult to apply to the 30
Doradus region.

Dopita (1980) has modelled the interaction of an OB star mass loss
wind with a collapsing neutral cloud and finds that a standing shock
front is set up at the interface. Neutral material is able to flow around
the surface of the mass loss bubble at this interface. If several mass
loss bubbles, from different primary star formation centres, overlap in
any region of a collapsing neutral cloud the standing shocks may supply
a means of focussing and compressing the flow of neutral material into
this common point. Dopita suggests that this model may be applicable to
the formation of the blue globular clusters in the Magellanic Clouds.
This structure of overlapping giant shells is precisely what is observed
in the 30 Doradus Nebula (Cantó et al. 1970), with the central compact
cluster lying at the common point of intersection. The model is clearly
consistent with the presence of slightly older generations of stars in
the surrounding regions and overcomes many of the difficulties encountered
in the Elmegreen and Lada theory.

The role of density waves in irregular barred spiral galaxies such
as the LMC (de Vaucouleurs and Freeman 1972) is difficult to assess. Two
points from the de Vaucouleurs and Freeman review are worth noting in
relation to star formation in the 30 Doradus region. (1) Comparison of
the LMC morphology with that of other Magellanic irregulars (e.g., NGC
4618 and NGC 4027) shows that the LMC morphology is largely shared by
other members of the class. The existence of large-scale order to the
"irregularity" is strong evidence for the existence of density-wave type
phenomena in these systems. (2) Classic barred spirals of earlier type, such as NGC 1300, exhibit very narrow straight dust lanes along the leading edges of the bar and have extensive regions of recent star formation, with many giant HII regions, at the ends of the bar where spiral arms begin. These phenomena are attributed to gas streaming along the bar away from the nucleus. Similar phenomena are also seen in the LMC. de Vaucouleurs and Freeman have identified an arc of dust absorption leading from the central bar to a region N-W of 30 Doradus, and 30 Doradus itself, at the eastern end of the LMC bar, is located in a region where giant HII regions and recent star formation are likely to be found in barred spiral galaxies. Both these facts indicate that density-wave type phenomena have probably played some role in creating suitable conditions for, if not actually in, the formation of the 30 Doradus complex.

VI. CONCLUSIONS

The major results of this investigation can be summarized as follows:

(1) The blue stellar population in the compact central cluster of 30 Doradus, among which are the 30 Doradus Wolf-Rayet stars, formed less than \(-10^6\) yr ago. The M supergiant population formed in an earlier star formation event in the same region of space \(-10^7\) yr ago. The present supernova rate for the older population is \(-5\) S.N. per \(10^6\) yr within the 2 \(\mu\)m survey region of HTR.

(2) Mass loss rates for the luminous 30 Doradus Wolf-Rayet stars are comparable with those of galactic Wolf-Rayet stars despite a difference of \(-3\) mag between the mean luminosities of the samples compared. These high mass loss rates place severe upper limits of \(-10^6\) yr on the ages of the Wolf-Rayet stars.
(3) The colour separation of spectroscopic luminosity class Ib and Ia M supergiants in the (J-H)$_o$ vs (H-K)$_o$ plane in both the Galaxy and the LMC is due, at least in part, to the positive luminosity dependence of the infrared CN absorption bands in these stars.

(4) The 30 Doradus M supergiants occupy anomalous positions in the (J-H)$_o$ vs (H-K)$_o$ plane relative to galactic M supergiants of the same luminosity. This result is interpreted as due to metal deficiency in the 30 Doradus supergiants through the effects of weaker CN absorption on the broad band infrared colours of these stars.

(5) CO band strengths in the 30 Doradus M supergiants are significantly weaker than in galactic supergiants of the same temperature. This is consistent with the lower metallicity for these stars suggested from their broad band colours.

(6) Water vapour absorption has been discovered in the 2 µm spectrum of the M supergiant Dor IR 6.

(7) The Magellanic Cloud blue globular clusters are similar to the 30 Doradus central cluster in size, mass, age, and concentration, in addition to having both formed in association with larger star formation events.

(8) Sequential OB star formation as encountered in the Galaxy is not applicable to the 30 Doradus region. In view of the present structure of the 30 Doradus region and the results of this paper, we favour the theory of Dopita (1980) for the interaction of a stellar wind flow with a collapsing neutral cloud as a likely mechanism for the formation of the 30 Doradus central cluster.
ACKNOWLEDGEMENTS

We wish to thank Dr. T.J. Jones for assistance at the telescope and critical appraisal of the manuscript and Dr. P.R. Wood for useful discussions on the giant branch evolution of massive stars. P.J. McGregor is the holder of an Australian Commonwealth Postgraduate Research Award. We thank an anonymous referee for perceptive comments which led to considerable improvements in the manuscript.
THE NATURE OF INTERSTELLAR EXTINCTION IN 30 DORADUS

Anomalous extinction with a value of $R = \frac{A_V}{E(B-V)}$ in excess of the normal galactic value of 3.1 has been reported for the central regions of a number of galactic HII regions (e.g., η Carina region ($R = 4.7 \pm 0.5$), Herbst (1976); Orion Nebula ($R = 5.2$), Johnson (1977)). Detailed study of the Carina region has shown that the anomalous extinction is confined to a region within ~20 pc of the nebula centre (Forte 1978). Theoretically these higher than normal values of $R$ can be explained by an increase in the relative numbers of larger than normal size dust particles in the vicinity of the nebula. Two mechanisms have been suggested for achieving this situation; (1) grain growth by accretion (Carrasco, Strom and Strom, 1973); and (2) selective evaporation of the mantles of small grains (Herbst 1976).

Although there is still some debate over its precise form, the ultraviolet extinction law in the central region of the 30 Doradus complex is undoubtedly anomalous (Borgman, van Duinen and Koornneef, 1975; Borgman and Danks 1977; Koornneef 1978). Both the general shape of the ultraviolet extinction and the strength of the 2200 Å feature differ from the normal galactic extinction law. Israel and Koornneef (1979) and Faulkner (1967) have both reported anomalous optical extinction in 30 Doradus with values of $R = 6.5$ and 7 respectively, however both these determinations rely on comparisons of the Balmer line photometry of Faulkner (1967) with various measurements of the nebula radio flux. The reality of these extremely high values of $R$ can be questioned on two counts. Firstly, Israel and Koornneef (1979) point out that the values of $R$ derived in this way will be overestimates if the gas and dust are well mixed. Secondly,
the absolute accuracy of Faulkner's (1967) Balmer line photometry is in some doubt. This second point requires further explanation. The basic observational material on which Faulkner's distribution of Balmer line emission in 30 Doradus is based is an Hα photographic plate. Calibration of this plate in terms of absolute fluxes at Hα and Hβ relies on a comparison of spectral scans near Hβ at eight positions in the nebula with scans of absolute flux standard stars (Faulkner and Aller 1965), an assumed ratio of I(Hα)/I(Hβ) = 2.61 (the presently accepted value is ~2.87 (Osterbrock 1974)) and an assumed reddening distribution derived from the I(HY)/I(Hβ) ratios at the eight spectral scan positions with the assumption that the absorbing dust and nebula gas are well mixed. The procedure (and its associated uncertainty) is sufficiently complex that a new and independent determination of the Hβ flux distribution in 30 Doradus seems warranted.

A further method for probing the nature of the extinction in the outer parts of the 30 Doradus Nebula is provided by the heavily reddened Cepheid, HV 2749, which lies only 15 arcmin (~250 pc) from 30 Doradus. Gascoigne (1969) obtained a value of $R = 2.8 \pm 0.25$ for this star after deriving its intrinsic colours from the Cepheid P-L and P-C relations. If the spatial distribution of extinction in 30 Doradus is similar to that seen in its closest galactic equivalent, the η Carina Nebula, this precise determination of $R$ for the outer region of the nebula may however not be appropriate to the inner regions of the nebula where many of the stars studied in the present paper lie.

In view of the uncertainties in the values of $R$ determined from Faulkner's (1967) photometry, we feel that the case for anomalous optical/infrared extinction in 30 Doradus with values of $R$ as high as 6.5 - 7 is not at all well founded at the present time. However, sufficient evidence
exists for larger than normal values of $R$ in other similar HII regions that the possibility of such anomalies also occurring in 30 Doradus cannot be excluded. Consideration must therefore be given to the possible effects of these anomalies on the major results of this paper.

An indication of these effects can best be obtained by considering the possibility that the extinction law in 30 Doradus is as extreme as the anomalous extinction law found in $\eta$ Carina. Using the data of Forte (1978) we plot $E(B-V)$ vs $E(V-I)$ and $E(V-R)$ vs $E(V-I)$ for stars in the $\eta$ Carina region in Figures Al-1(a) and Al-1(b). The solid lines in these figures represent the appropriate normal galactic field relations found by Forte for each plane. The Carina extinction is clearly anomalous in the $E(B-V)$ vs $E(V-I)$ plane but is equally clearly in good agreement with the normal galactic slope in the $E(V-R)$ vs $E(V-I)$ plane. The implication of this result is that the shape of the extinction law in $\eta$ Carina follows the normal galactic law between $V$ (-5500 Å) and $I$ (-9000 Å), but deviates from the galactic law at $B$ (-4400 Å). This deviation is in the sense to make the absorption at $B$ in $\eta$ Carina lower than found elsewhere and so is in the correct sense to explain the larger than normal values of $R$ found for this nebula. This conclusion has been extended by the work of Smith (1980) who showed that the extinction in $\eta$ Carina is normal from $V$ through to at least $K$ (2.2 µm) and that the anomalous value of $R$ can be explained entirely by anomalous extinction in the $B$ filter. The same result of normal infrared extinction associated with possibly anomalous short wavelength extinction has also been found in several recent detailed studies of dark cloud complexes (see review by Hyland 1980).

In the present paper the absolute value of the extinction in various parts of the 30 Doradus Nebula has been set using the distribution of H$\beta$ absorption found by Mills, Turtle and Watkinson (1978), which is in fact
FIG. AI-1 - (a) E(B-V) vs E(V-I) diagram for early type stars in the η Carina Region (Forte 1978). The solid line represents the normal galactic extinction line. The extinction law in the η Carina Region is clearly anomalous in this plane (dashed line).

FIG. AI-1 - (b) E(V-R) vs E(V-I) diagram for early type stars in the η Carina Region (Forte 1978). The solid line represents the normal galactic extinction line. The extinction law in the η Carina Region is identical to the galactic law for wavelengths longward of the V passband.
Based on the work of luminosity calculations (157), which have been reported by several authors, the correlation for a normal color excess in Table 4.1 for an observed system is presented.

This allows us to show that the choice of a particular set of observations can be justified. Using the normal galactic distribution of stars of all ages, we have shown that the distribution of stars of all ages, with the bias in selecting the right regions, leads to an intrinsic bias which is as large as 0.37 and 0.38, respectively, with the bias being close to zero for the blue stars.

As the result of a detailed study of the following systems, we have found that all the major conclusions are correct and independent. Indeed, it can be seen by examining their effects on the data that there is a tendency for the red stars to have a higher color excess. This is reflected by the 0.10 mag, which affects the color excess $\Delta E$ and hence $E_{V-I}$ for the red stars.
based on the same Hβ isophotes of Faulkner (1967) which have been ques-
tioned above. If the extinction law in 30 Doradus follows the η Carina law, some fraction of the anomalous blue extinction will also be felt at Hβ. Assuming the anomalous extinction law is linear between V and B allows us to compute reddening corrections to the observed colours given in Table 1 for an η Carina type extinction law. These corrections are shown in Table AI-1 for an absorption of 2 mag at Hβ, along with the corresponding corrections for a normal galactic extinction law (Lee 1970). It can immediately be seen that the choice of extinction law is only significant for the V magnitudes and B-V colours.

B-V colours for the two Wolf-Rayet stars Dor IR 16 and 21 when dereddened using the normal galactic extinction law with the Hβ absorption distribution of Mills et al. are bluer than any defined in the UBV system. Using the R = 5 law leads to intrinsic B-V colours for these stars of -0.37 and -0.36, respectively, which are near the blue limit for permitted B-V colours. For this reason at least, an η Carina-type extinction law appears to give more reasonable results in 30 Doradus than the normal galactic law and has consequently been adopted for this work. In the following we demonstrate that all the major conclusions of this paper are independent of this choice.

The effects of an anomalous extinction law on the major conclusions of this paper can be seen by examining their effects on the figures which have been presented:

(1) Figure 2 would not be significantly altered by the use of a normal galactic extinction law rather than the anomalous one which has been used. As can be seen from Table AI-1, A_V and hence M_BOL for the blue stars is altered by ≤ 0.10 mag, while the effect on A_K and hence M_BOL for the red
stars is negligible. Because of the qualitative nature of the discussion relating to this figure, none of the associated results are affected.

Table AI-1

<table>
<thead>
<tr>
<th>R</th>
<th>$A_{H\beta}$</th>
<th>$A_V$</th>
<th>$E_{B-V}$</th>
<th>$A_K$</th>
<th>$E_{J-K}$</th>
<th>$E_{H-K}$</th>
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<tr>
<td>3.6</td>
<td>2.0</td>
<td>1.68</td>
<td>0.47</td>
<td>0.18</td>
<td>0.28</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>1.78</td>
<td>0.36</td>
<td>0.20</td>
<td>0.29</td>
<td>0.10</td>
</tr>
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</table>

(2) The $(B-V)_0$ colours in Figure 3 are moved up to $-0.15$ mag bluer if a galactic law is used. As discussed above the $(B-V)_0$ colours for two stars then become too blue. The effect of the choice of extinction law on the $(J-K)_0$ colours which measure excess free-free emission is negligible. The net result of adopting a galactic extinction law is therefore to increase the Wolf-Rayet star $E_f(J-K)$ values by $-0.1$ mag which corresponds to an increase in mass loss rate by a factor of $<2$ for these stars. The uncertainties involved in the type of mass loss rate determination employed are larger than this factor. Since the reddening line in the $(B-V)_0$ vs $(J-K)_0$ plane is approximately parallel to the mean line for normal supergiants in this plane, the derived excesses are largely independent of the magnitude of the extinction used.

(3) Similarly in the $(J-H)_0$ vs $(H-K)_0$ plane (Fig. 6), the reddening corrections are independent of the choice of extinction law and the separation found between galactic and LMC supergiants of the same luminosity is orthogonal to the direction of interstellar reddening.
Finally, in the (CO)$_0$ vs (J-K)$_0$ plane (Fig. 11), the reddening corrections are independent of the choice of extinction law, however the separation between galactic and LMC supergiants shown in this figure does depend on the magnitude of the J-K absorption adopted. In view of the tight nature of the sequence formed by the 30 Doradus late-type supergiants in Figure 11 we feel that it is unlikely that the applied reddening corrections are significantly in error.
APPENDIX II

COMPUTATION OF BROAD BAND INFRARED COLOURS

The rigorous computation of absolute synthetic infrared colours from first principles is a formidable task and one which has not been attempted here. Instead we have computed relative broad band colours which have been placed on an absolute scale by identifying a particular model with a particular star and equating their colours in the same way that empirical photometric systems are usually defined relative to a primary standard of known absolute flux.

The technique adopted here uses the grid of line blanketed model atmospheres of Bell et al. (1976) (3750 ≤ Te ≤ 6000K, 0.75 ≤ log g ≤ 3.0), supplemented by six log g = 0.0 models (Te = 4000, 4250, 4500K; [A/H] = 0.0, -0.5) computed in the same way by B. Gustafsson. Extrapolation outside this grid to lower temperatures (i.e., 3600K) may introduce additional errors in the synthetic colours since no TiO opacity was included in the original model calculations. The flux distributions from 0.8 µm to 3.0 µm for these models have been recomputed at 0.02 µm resolution using the model atmosphere program ATLAS5 (Kurucz 1970). Sources of continuous opacity were essentially the standard ATLAS5 continuous opacities (bound-free and free-free opacity of HI, H₂⁺, H⁻, CI, MgI, AlI, and SiI, He⁻ free-free, Rayleigh scattering from HI, HeI, and H₂, and electron scattering) plus some other opacities for which routines were available at Mount Stromlo (Rayleigh scattering from CI (Tarafdar and Vardya 1969), C⁻ bound-free and free-free (Myerscough and McDowell 1964, 1966), and H₂⁻ free-free (Somerville 1964, Carbon, Gingerich and Latham 1969)). The H⁻ ion opacity forms ~80% of the total infrared continuum
opacity in the models considered. The importance of various sources of line opacity in late-type stars will be discussed in Appendix III.

The 45 atomic and molecular species in Table AII-1 were included in the molecular equilibrium calculations. Dissociation energies for the molecular species are also listed. Test calculations involving a large number of species showed this list to contain all the atomic and molecular species important in determining the molecular equilibrium in late-type supergiant stars.

<table>
<thead>
<tr>
<th>Atomic and Molecular Equilibrium Species</th>
<th>D_o (eV)</th>
<th>D_o (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+ Mg+ Ca+ Ca+ H- H2 Ti+ CH Si+ Fe+</td>
<td>0.755 CO</td>
<td>11.102</td>
</tr>
<tr>
<td>H+ Al+ Ti+ CH Si+ Fe+ C+ Si+ Fe+</td>
<td>4.467 NO</td>
<td>6.505</td>
</tr>
<tr>
<td>H+ Al+ Ti+ CH Si+ Fe+ C+ Si+ Fe+</td>
<td>3.469 C2</td>
<td>6.115</td>
</tr>
<tr>
<td>C+ Si+ Fe+ CN MgH</td>
<td>7.893 CO2</td>
<td>16.566</td>
</tr>
<tr>
<td>C+ Si+ Fe+ HCN MgH</td>
<td>12.833</td>
<td>1.996</td>
</tr>
<tr>
<td>N+ S+ OH SiO</td>
<td>4.380</td>
<td>8.240</td>
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<tr>
<td>O+ H2O SiS</td>
<td>9.497</td>
<td>6.375</td>
</tr>
<tr>
<td>Na+ K+ HCO SC</td>
<td>12.272</td>
<td>7.849</td>
</tr>
<tr>
<td>Na+ K+ N2 SH</td>
<td>9.758</td>
<td>3.599</td>
</tr>
<tr>
<td>Mg Ca NH TiO</td>
<td>3.209</td>
<td>6.830</td>
</tr>
</tbody>
</table>

Total fluxes through pass bands chosen to imitate the MSO J, H, and K pass bands as closely as possible were computed from the model flux distributions. The adopted J, H, and K pass bands were formed by multiplying the actual MSO filter transmission, a detector response proportional to wavelength and an approximation to the sky transmission...
at Siding Spring Observatory. These relative responses are shown separately in Figure AII-1 along with the Johnson J and K filter transmissions, the AAO J filter transmission and the computed flux distribution for the $T_e = 4000K$, log $g = -0.74$, solar abundance model. CN bands are clearly evident in all three filter pass bands. The greater redward transmission of the MSO J filter relative to the Johnson and AAO J filters can also be seen.

The response characteristics of both PbS and InSb detectors are proportional to wavelength through the region of interest because for both detectors the signal voltage is proportional to the number of incident photons. We do not distinguish further between the detailed response characteristics of individual detectors.

The reflection efficiencies of the gold and aluminium surfaces in the telescope/photometer optical train and the transmission characteristics of the sapphire dewar window and field optics are essentially flat through the 1-3 µm region and have not been included in the adopted pass bands.

The inclusion of a sky transmission function in the adopted filter transmission functions is not strictly a correct procedure. The effects of sky transmission on empirical infrared photometry are removed to some extent by correcting linearly for atmospheric extinction. However, telluric absorption in the infrared is predominantly due to saturated and unsaturated molecular features of $H_2O$ and $CO_2$ and the different rates of change of these features with airmass cause the relation between infrared atmospheric extinction and airmass to be non-linear (Jones 1969, Mould 1976, Manduca and Bell 1979). Serious errors can therefore result when comparing absolute fluxes measured from above and below the Earth's atmosphere. Since many saturated telluric features are present at all
FIG. AII-1 - Transmission functions for infrared photometric systems. The frames, from bottom to top, show (1) the actual MSO JHK filter transmission functions, (2) the J and K filter transmission functions for the Johnson (1965) system (solid line) and the AAO J filter transmission function (dashed line), (3) the adopted sky transmission function and a detector response function proportional to wavelength, and (4) the compute flux distribution for the solar abundance model with $T_e = 4000K$ and $\log g = -0.74$. The positions of CN absorption bands are marked. The greater redward transmission of the MSO J filter compared to the Johnson J filter can be clearly seen.
airmasses greater than unity and they significantly modify the infrared pass bands, we have adopted the hypothesis that extinction corrections to empirical photometry adequately correct for unsaturated atmospheric features while the features remaining saturated at unit airmass act only to modify the pass bands used from the ground. These modifications to the filter pass bands can be important and must be included in theoretical calculations. A smoothed version of the Kitt Peak summer sky transmission (Manduca and Bell 1979) has been used to approximate the saturated features in the summer sky transmission at Siding Spring Observatory.

The zero point of the theoretical colour system was set by comparison of the theoretical colours for α Ori and α Boo with their empirical colours on the MSO system (transformed from Lee (1970)). The adopted zero point corrections (ΔJ-H = -0.16, ΔH-K = 0.10) are the mean values of the corrections found for these two stars. Zero point corrections for α Ori, α Boo and the Sun, along with the adopted model parameters for these stars, are shown in Table AII-2. Significant differences exist between

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the corrections based on $\alpha$ Ori and $\alpha$ Boo and the corrections based on the Sun. This is most likely due to neglected opacity sources in the model flux computation. The $\alpha$ Ori/$\alpha$ Boo corrections are more suitable for the present work since these stars are more closely related to the stars under investigation. The above procedure has been preferred over the usual method using $\alpha$ Lyr because $\alpha$ Lyr cannot be adequately observed from Mt. Stromlo and the Bell et al. grid does not contain a model atmosphere appropriate to this star. Theoretical colours on the MSO system were transformed to the Johnson system using the empirically determined transformations.
In oxygen-rich late-type supergiant stars the CO and CN molecules have important absorption bands in the infrared spectral region and, in very cool stars, TiO may also become important. Atomic line blanketing is also present, but of less importance. In attempting to understand the observed separation of luminosity class Ia and Ib M supergiants in the $(J-H)_0$ vs $(H-K)_0$ plane, it has therefore been necessary to estimate the effects of each of these opacity sources on the broad band infrared colours of late-type stars.

The first-overtone bands of CO at 2.3 µm are known from narrow band photometry (Baldwin, Frogel and Persson 1973) and infrared spectroscopy (Hyland 1974a) to show a moderate, positive luminosity dependence and to be confined to the K pass band at wavelengths ≥ 2.3 µm. The greater band strengths in supergiant stars therefore act in a sense to make supergiant $(H-K)_0$ colours bluer than in giant stars of the same temperature. This opposes the sense of the observed colour separation we attempt to explain.

The magnitude of the effect can be estimated from narrow band photometry. The difference in CO index between giant and supergiant stars at spectral type M0 is ~0.08 mag in the Frogel et al. (1978) index (transformed from Baldwin et al.). Following Cohen, Frogel and Persson (1978), we estimate the effect of CO absorption on the K magnitude to be ~20% of the CO index since the CO bands occupy ~20% of the K pass band. The effect of the stronger 2.3 µm CO bands in M supergiants is therefore to make $(H-K)_0$ ~0.02 mag bluer than in M giant stars. This shift is insignificant in comparison with the observed colour separation.
The second-overtone bands of CO occupy -80% of the H pass band but their mean absorption coefficient is a factor of -100 lower than for the first-overtone bands (Kunde 1968). This lower line opacity is offset in part by lower continuum opacity in the H pass band and by possible saturation in the first-overtone bands, however it is unlikely that the second-overtone bands will make a significant contribution to the observed colour difference. Consequently, no CO opacity has been included in the synthetic broad band colour calculations.

At optical wavelengths, TiO opacity is only important in stars with effective temperatures \( \leq 4000K \). TiO bands of the singlet \( \phi(b^1\Pi - d^1\Xi^+) \) and \( \delta(c^1\Phi - a^1\Delta) \) systems are present in the infrared region. The electronic oscillator strengths for all the singlet systems are lower than those of the triplet systems occurring in the optical spectral region by at least a factor of 10 (Krupp, Collins and Johnson 1978). Furthermore the singlet \( \phi \) and \( \delta \) systems of TiO originate from excited \( d^1\Sigma \) and \( a^1\Delta \) lower electronic states, respectively, resulting in a further reduction in band strength relative to the triplet systems. Consequently, TiO is not expected to be an important source of infrared opacity in the stars studied here and has not been included in the present calculations. Johnson and Mendez (1970) have identified TiO bands longward of 3 \( \mu \)m in the spectra of several late-type stars.

Atomic line blanketing was also omitted since this opacity source has its main effect in the blue spectral region.

Wing and Spinrad (1970) have identified bands of the red system of CN in the 1.1 \( \mu \)m - 2.5 \( \mu \)m regions of published M supergiant and carbon star spectra and find that their strengths are consistent with the strengths of red CN features in the 1 \( \mu \)m region. They claim that the CN molecule is probably the most important bound-bound opacity source in
K and M supergiants. CN bands are present in each of the J, H and K pass bands (e.g. Phillips and Leung 1973) and are known to have a positive luminosity dependence at optical wavelengths in M supergiants. For these reasons, it is expected that the infrared CN absorption bands may significantly affect the infrared colours of luminous M supergiants.

Line absorption due to the CN molecule has been modelled in an approximate way using tabulated straight mean $^{12}$C$^{14}$N opacities over 100 cm$^{-1}$ wide regions (Johnson, Marenin and Price 1972). The deficiencies of the straight mean opacity formulation have been discussed at length in the literature (e.g. Carbon 1974, 1979); the method is prone to underestimating the model flux and hence to over-estimating the strengths of spectral features. It, nevertheless, offers a convenient way of including the CN opacity in a first approximation. No means is available for testing the effects of variations in the microturbulent velocity on the CN band strengths in this formulation.
REFERENCES


CHAPTER 3

A PHOTOMETRIC COMPARISON OF LATE-TYPE CLUSTER SUPERGIANTS IN THE MAGELLANIC CLOUDS AND THE GALAXY

P.J. McGregor and A.R. Hyland

ABSTRACT

Broad band infrared photometry and 2.3 μm CO indices have been measured for 20 late-type supergiants in young Magellanic Cloud blue globular clusters and 12 late-type supergiants in southern galactic open clusters. New photo-electric B and V data for most of these stars are also presented. These data allow comparisons to be made between the infrared properties of late-type supergiant stars in the Galaxy and the Large and Small Magellanic Clouds.

The broad band infrared colours of the Magellanic Cloud blue globular cluster stars differ from those of galactic stars of the same luminosity in exactly the same way as found previously for the M supergiants in the 30 Doradus complex in the LMC. These differences are thought to be due to CN abundance deficiencies in the Magellanic Cloud stars. The galactic supergiant CO indices allow a mean galactic supergiant relation to be defined in the \((CO) \gamma \) vs \((J-K) \gamma \) plane. At a given \((J-K) \gamma \) colour the LMC supergiant CO indices are \(-0.04\) mag weaker than this mean galactic value. The 30 Doradus supergiants follow the same sequence in the \((CO) \gamma \) vs \((J-K) \gamma \) plane as the other LMC supergiants.
A preliminary theoretical analysis shows that the CO indices in the LMC supergiants are consistent with these stars being deficient in heavy elements by a factor of -3. The supergiants in the SMC cluster NGC 330 are hotter than the LMC supergiants and show more pronounced CO deficiencies (-0.1 mag).

Comparisons are made between the giant branch morphologies of each cluster and recent evolutionary tracks for massive stars. The Magellanic Cloud cluster giant branch morphologies can only be reconciled with the cluster end-main sequence masses (-14 $M_\odot$) if star formation in the blue globular clusters has occurred over a time span of $10^7$ yrs.

I. INTRODUCTION

Despite considerable effort (Przybylski 1968, 1971, 1972, 1979; Wares, Ross and Aller 1968; Wolf 1972, 1973; Osmer 1973; Fry and Aller 1975) our knowledge of the young Population I stellar abundances in the Magellanic Clouds remains sparse. The Large Magellanic Cloud (LMC) is generally considered to be deficient in heavy elements by a factor of -3 and the Small Magellanic Cloud (SMC) deficient by up to a factor of -10. Beyond this we are confronted by a range of results for the abundances of different stars as well as conflicting results by different workers for the abundances of a few individual stars. Przybylski (1979) has suggested from his curve of growth analyses that a range in abundance may exist among young Population I stars in the LMC. This suggestion is not supported by HII region abundance analyses (Pagel et al. 1978) or by Cepheid variable results (Gascoigne 1980).
Investigations of the infrared properties of late-type supergiant stars are a potential means of obtaining information about the chemical abundances of young Population I objects in the Magellanic Clouds. In addition, infrared photometry is the only means by which accurate data can be obtained for the bolometric luminosities and effective temperatures of these late-type stars. This information is essential to the improvement of our empirical knowledge of the late stages of the evolution of massive stars. The study of late-type Magellanic Cloud supergiants at infrared wavelengths is therefore of two-fold importance.

The late-type supergiants in young Magellanic Cloud blue globular clusters form a homogeneous sample of stars which is well suited to these studies. The blue globular clusters have the advantages of known reddening, distance, and age as well as containing large numbers of stars in the red supergiant region of the colour-magnitude diagram (CMD). As will be shown in the following, the luminosities of these stars place them in an important position in the CMD in the region of overlap between high mass (M/M_☉ ≥ 10) and intermediate mass (3 ≤ M/M_☉ ≤ 9) giant branch stars. Furthermore, on the basis of previously published optical photometry (Robertson 1974a), it was anticipated at the outset of this research that the atmospheric parameters of the Magellanic Cloud supergiants would be similar to the atmospheric parameters of the giant stars in recent infrared studies of galactic globular clusters (Cohen, Frogel and Persson 1978; Frogel, Persson and Cohen 1979; Persson et al. 1980). If this prediction had proved to be correct, abundance information could have been obtained with relative ease by direct comparison with galactic globular cluster data. In fact, the Magellanic Cloud
stars have significantly lower surface gravities and lower effective temperatures than galactic globular cluster giants and such direct comparisons have not been possible.

The Magellanic Cloud blue globular clusters have been the subjects of a large number of CMD investigations in the past. It has been known for many years that their CMD's differ in detail from the diagrams characteristic of young open clusters in our galaxy (Arp 1959a, b). In particular, clear differences can be seen in the numbers and distributions of late-type supergiant stars in the CMD's of galactic and Magellanic Cloud clusters of the same age (Hagen and van den Bergh 1974). It has generally been speculated that these differences are due to heavy element deficiencies in the Magellanic Cloud stars.

Feast (1979) found spectroscopic evidence for metal deficiencies in the red supergiants of the SMC blue globular cluster NGC 330 in that the blue CN bands appeared weak and the hydrogen lines appeared strong in these stars. Feast assigned spectral types of -G5Ib to seven of the stars studied, although their optical colours indicate later types (B-V - 1.3 - 1.6 mag). Similarly, Feast classified late-type supergiants in the LMC blue globular cluster, NGC 2004, as -KO1b (B-V - 1.5 - 1.6 mag). Janes and Carney (1977, 1980) also claim from DDO photometry of four late-type stars in NGC 330 that [Fe/H] ≤ -1.3 for this cluster, however this result remains unconfirmed.

Humphreys (1979a, b) has made spectroscopic studies of M supergiants in various parts of both Magellanic Clouds. She found no clear evidence for metal deficiency in the LMC stars, although she did find a shift in the spectral-type distribution to earlier spectral types in the SMC which is most likely due to metal abundance deficiencies in these late-type
stars. McGregor and Hyland (1980, hereafter MHl) obtained infrared measurements of M supergiants in the immediate vicinity of the LMC giant HII region, 30 Doradus. The broad band infrared colours of these stars, and possibly those of other more luminous, variable LMC supergiants (Glass 1979), were found to deviate from the colours of galactic stars of the same luminosity. This effect was attributed to metal deficiency in the LMC stars through the effects of abundance on the infrared CN bands lying predominantly in the H pass band. In addition the 2.3 μm CO indices for the 30 Doradus supergiants were weaker than in galactic supergiants of the same temperature. There is therefore considerable evidence to suggest that abundance anomalies are present in Magellanic Cloud late-type supergiant stars and that these anomalies can be effectively studied using infrared photometry.

The lack of galactic comparison stars with well determined intrinsic properties has, to date, limited the usefulness of late-type supergiants for this type of study. To overcome this problem we have embarked on a project to define observational and intrinsic properties for a larger sample of galactic late-type supergiant stars, in addition to the Magellanic Cloud studies. Unfortunately, it has been necessary to exclude the many M supergiants in the northern galactic clusters h and X Persei from parts of the discussions presented in this paper because no H magnitudes are available in the literature for these cluster supergiants. JHK data for a number of M supergiants in the field region surrounding the h and X Persei clusters have been presented by Lee (1970) and are used for comparison purposes in some sections of the paper.

1 MHl = Chapter 1
The observations presented in this paper are described in §II. In §III reddening corrections and distance moduli for each cluster are discussed and the derivations of end-main sequence stellar masses, stellar effective temperatures and bolometric corrections explained. In §IV we present and discuss the evidence for abundance differences between the Magellanic Cloud and galactic stars, while the cluster giant branch morphologies and the evolutionary status of the cluster supergiants are discussed in §V. Our conclusions are summarized in §VI.

II. OBSERVATIONS

Broad band JHK infrared photometry and narrow band filter photometry of the 2.3 µm first-overtone CO bands have been measured for 20 Magellanic Cloud late-type supergiants in blue globular clusters and 12 galactic late-type supergiants in young open clusters. CO indices have also been measured for 8 stars from 2 µm circular variable filter (CVF) spectra. New optical (B,V) photometry has been obtained for most program stars.

The Magellanic Cloud stars were selected from the photographic photometry of Robertson (1974a) on the basis of two criteria: (1) they must be brighter than B = 16 mag and redder than B-V = 1.0 mag, (2) they should be measurable with a 30 arcsec diameter aperture without contamination from nearby resolved stars. The first criterion restricts the program clusters to only the youngest blue globulars in the Magellanic Clouds, which contain the brightest stars. The clusters studied are NGC 330 (SMC), NGC 2100 (LMC) and NGC 2004 (LMC). The CMD for each of these clusters (Robertson 1974a) broadly resembles that of h and χ Persei in our Galaxy. In addition, one star from NGC 1850 (LMC) is also included.
For a few program stars, criterion (2) could not be strictly met. The uncertainties thereby introduced will be discussed below. Nomenclature for the Magellanic Cloud stars has generally been taken from Robertson (1974a). The star NGC 2100/W44 has been identified by Westerlund (1961). NGC 2004/X lies -2 arcmin east of the cluster centre.

The galactic stars studied are all late-type supergiants in southern galactic open clusters. The galactic clusters studied are NGC 2323, NGC 2439, NGC 3293, NGC 3766, NGC 4755, and NGC 6067. These clusters are of comparable age to, but are far less populous than, the Magellanic Cloud clusters. An exception is NGC 6067 which contains a large number of K supergiants (Thackeray, Wesselink and Harding 1962) and is expected to be somewhat older than the Magellanic Cloud clusters.

(a) Infrared Photometry

The Magellanic Cloud infrared photometry was obtained on the 4m Anglo-Australian Telescope (AAT) during the summer of 1978/79 using the Mount Stromlo Observatory (MSO) infrared photometer with a 10 arcsec aperture and a beam separation of 26 arcsec, generally in an E-W direction. An InSb photodiode detector was used for all observations. The observational technique and standardization were as described in Mould and Hyland (1976) and MHL. Special care was taken in the narrow band CO observations to ensure that frequent observations of nearby standard stars were made along with the cluster star observations.

In two cases another faint ($m > 3$ mag) resolved star was also present within the 10 arcsec aperture, in violation of selection criterion (2) above. Since in both cases the offending stars were blue objects, their presence will have no significant effect on the infrared photometry of the luminous red supergiants. Similarly, uncertainties in the infrared photometry due to possible inexact cancellation of
unresolved cluster background radiation will be negligible in these blue clusters. [Red main sequence stars (e.g., later than G spectral type) are $\gtrsim 6$ mag fainter than the red supergiants in these clusters.]

The infrared photometry of the galactic stars was obtained on the 40-inch (1 m) telescope at Siding Spring Observatory using the same MSO photometer. The aperture and beam separation parameters for these observations were 34 arcsec and 85 arcsec, respectively. The same careful observing technique was used for the galactic cluster star measurements. Background contamination was generally not a problem in these clusters, which are less populous and present a far larger area on the sky than the Magellanic Cloud clusters.

The instrumental photometric system for the broad band observations has been described in MH1. All broad band infrared photometry presented in this paper has been transformed from the MSO system to the Anglo-Australian Observatory (AAO) system (which closely resembles the original Johnson system (Johnson 1965)). The narrow band CO filters are similar to those of Baldwin, Frogel and Persson (1973), having central wavelengths and bandwidths at 77K of 2.20; 0.09 and 2.33; 0.10 µm. We note that our 2.3 µm filter is centred sufficiently redward of the Baldwin et al. filter (although not as red as the Frogel et al. (1978) filter) for its pass band to lie totally within the CO absorption feature. This allows an increased sensitivity to the feature over the Baldwin et al. filter which measured a contribution from the blueward continuum. A CO index is defined from the filter photometry in the same way as has been done by Baldwin et al. and Frogel et al. (1978). The early-type stars BS 3314 and BS 2015 were used as primary standards for the CO indices ($CO_{\text{MSO}}$), having indices of $+.005$ and $-.005$, respectively. The transformation
between CO indices measured on this system and those of Frogel et al. (1978) \((CO_F)\) and Baldwin et al. \((CO_B)\) was determined from observations of common stars to be

\[
CO_F = 1.25 \ CO_{MSO} = 1.75 \ CO_B.
\]

All photometric CO indices presented in this paper have been transformed from the MSO system to the Frogel et al. (1978) system using this transformation. The infrared photometry for the SMC, LMC and galactic stars is presented in columns (1) through (6) of Tables 1, 2 and 3, respectively. Columns (4) and (6) in each table indicate, respectively, the numbers of broad band and narrow band measurements of each object obtained.

The 2 \(\mu m\) CVF spectra were obtained on the AAT using a 2\% resolution CVF in the AAO infrared system (Barton and Allen 1980). A method for measuring CO indices from higher resolution CVF spectra was described in MH1. CO indices \((CO_{CVF})\) measured from our lower resolution spectra using the same method are presented in column (7) of Tables 1, 2 and 3. CO indices measured from CVF spectra of this resolution have been found to be numerically equal to Frogel et al. (1978) indices.

In most cases it was possible to continue the photometric measurements until a statistical uncertainty of less than 0.01 mag was obtained. Agreement between standard stars on each night indicated that the uncertainty in a single measurement of either the broad band colours or narrow band CO indices was generally less than 0.02 mag. The estimated errors have been explicitly indicated in the appropriate tables when they exceed this value. Uncertainties in the CO indices measured from CVF spectra are expected to be comparable to the uncertainties in the corresponding photometric indices. These two measures of the CO band strength agree to within this uncertainty.
### TABLE 1
LMC PHOTOMETRY

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### Notes
- Notes 1 to 12, 14, and 15 refer to specific identifiers.
- Notes 1 to 12, 14, and 15 are not explicitly listed in the table.
### Table 2

**Galactic Cluster Photometry**

<table>
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<tr>
<th>Name</th>
<th>K</th>
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<th>H-K</th>
<th>Color</th>
<th>Cluster</th>
<th>V</th>
<th>B-V</th>
<th>Spectral Type</th>
<th>Notes</th>
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<td>(1.78)</td>
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<td>(1.70)</td>
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**Notes to Table 2**

1. Spectral type from Morgan and Keenan (1971)
2. Spectral type from Keenan (1971)
3. North of NGC 3766, membership uncertain
4. V, B-V and Spectral type from Thackeray et al.
(b) **Optical Photometry**

The new optical photometric data presented in columns (8) and (9) of Tables 1, 2 and 3 were measured on the 40-inch telescope at Siding Spring Observatory using a single channel photometer, standard Johnson filters, a 1P21 photomultiplier and E- and F- region standards from Cousins (1973). The number of measurements obtained for each object are listed in column (10) of each table. For most observations an 18 arcsec diameter aperture was employed, with a 9 arcsec aperture being used on a few occasions of comparatively good seeing. Sky positions were chosen to resemble the actual background conditions as closely as possible.

Since the compact Magellanic Cloud clusters consist predominantly of blue stars, it is to be expected that optical aperture photometry of their red supergiants will be affected to some extent by contamination from other resolved and unresolved cluster stars. Variations in the background brightness at the slightly different sky positions used for each measurement also affect the photometry. Standard errors for the tabulated mean values of the optical photometry have been included in Tables 1, 2 and 3 when in excess of 0.02 mag and give an indication of the magnitude of the latter effect. Variability in the red supergiants themselves may also contribute to the scatter between individual observations. In three cases (indicated by an asterisk in column (16) of Tables 1 and 2) nearby resolved stars (ΔV > 3 mag) were apparent on the original plates of Robertson (1974a) within the 18 arcsec aperture size. No attempt has been made to correct the optical photometry for the presence of these stars.

As mentioned in §II(a), no contamination problems were encountered in the galactic open clusters.
No new optical photometry has been obtained for the stars B42 and B23 in NGC 330, star C2 in NGC 2100 or any of the stars in NGC 6067. Published optical photometry has been taken from Robertson (1974a) for these Magellanic Cloud stars and from Thackeray et al. for the NGC 6067 stars and are shown enclosed in brackets in Tables 1, 2 and 3. A zero-point correction of 0.08 mag was added to Robertson's V magnitudes for the NGC 330 stars on the basis of comparisons of our optical colours for other NGC 330 stars with Robertson's values. No other systematic differences could be found between Robertson's photometry and the photometry presented here for NGC 330 and NGC 2100; however significant scatter exists in the comparisons which is most likely a result of the uncertainties discussed above and variability in the late-type supergiant stars.

III. ANALYSIS

(a) Reddening Corrections

The adopted reddening corrections for the Magellanic Cloud and galactic clusters are shown in Tables 4 and 5, respectively. The Magellanic Cloud cluster reddenings are taken from Robertson (1974a). Sources for the galactic cluster reddening are listed in Table 5. Adopted parameters for η and η Persei are also included in Table 5. The interstellar extinction law of Lee (1970) for galactic M supergiants has been used in this work. Reddening corrected photometry for the SMC, LMC and galactic supergiants are given in columns (11) through (15) of Tables 1, 2 and 3 respectively. (Throughout this paper, reddening corrected colours are represented by a subscript zero).
Table 4
Adopted Magellanic Cloud Cluster Parameters

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<th></th>
<th>E(B-V)</th>
<th>(m-M)$_o$</th>
<th>M$_{MS}$ (M$_o$)</th>
<th>M$_{Rob}$ (M$_o$)</th>
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</thead>
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Table 5
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<td>11.4</td>
<td>10</td>
<td>19</td>
<td>11</td>
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</tbody>
</table>

References

(1) Johnson et al. (1961)
(2) Hoag and Applequist (1965)
(3) Hoag et al. (1961)$^a$
(4) White (1975)$^a$
(5) Turner et al. (1980)
(6) Schild (1970)
(7) Sher (1965)$^a$
(8) Perry et al.$^a$
(9) Thackeray et al.$^a$
(10) Crawford et al.
(11) Wildey (1964)

$^a$ Mass determination based on CMD by these authors.
(b) **Distance Moduli**

Distance moduli for the LMC and SMC (Table 4) have been taken from Martin, Warren and Feast (1979) and Gascoigne (1974), respectively. Sources of galactic cluster distance moduli are references in Table 5. No correction has been made for the recent readjustment to the Hyades distance modulus (Hanson 1975) since several of the determinations are independent of the Hyades distance (Perry, Franklin and Landolt 1976, Crawford, Glaspey and Perry 1970) and the usual method of zero-age main sequence fitting is only moderately sensitive to the Hyades distance for these young clusters which have almost vertical upper main sequences. van den Bergh (1977) and Martin *et al.* have discussed the dependence of Magellanic Cloud distance moduli on the adopted Hyades distance modulus and find it to be small.

(c) **End-Main Sequence Stellar Masses**

The masses of stars at the top of the main sequence have been recomputed for each cluster using a relation between stellar mass and $M_v$ at the top of the main sequence which was derived from the evolutionary tracks of Robertson (1972) following the procedure of Robertson (1973). Unlike Robertson (1973) we have taken the top of the main sequence to be the point immediately below the characteristic break in the upper blue sequence of these young clusters in the CMD. The blue stars above this break are assumed to be evolved helium-core burning supergiants. Clearly the identification of the end-main sequence point in the CMD is a source of considerable uncertainty in the derived masses. Uncertainties in the mean cluster reddening and distance modulus also contribute to the final uncertainty, along with uncertainties in the bolometric corrections and the evolutionary tracks. Robertson (1973) has commented that
uncertainties in the evolutionary tracks due to variations in abundance should not lead to errors in the derived masses in excess of $-1M_\odot$. With these points in mind, we estimate that, given the assumption we have made about the nature of stars on the upper blue sequence of the CMD's of young clusters, the derived end-main sequence stellar masses should not be in error by more than $-20\%$. The main sequence masses for each cluster ($M_{\text{MS}}$) and references to the CMD's from which they were derived are given Tables 4 and 5 for the Magellanic Cloud and galactic clusters, respectively. The main sequence masses derived by Robertson (1973) for the same clusters ($M_{\text{Rob}}$) are also listed in these tables.

(d) Effective Temperatures

In MH1 we demonstrated the usefulness of $(J-K)_0$ as a temperature indicator in late-type giants and supergiants with metal abundances in the range $0.0 \geq [\text{A/H}] \geq -1.0$ by computing theoretical infrared colours for a range of model flux distributions which included CN opacity but neglected absorption due to the first-overtone CO bands in the K pass band. This omission should not invalidate the result for metal abundances in the range of solar to deficient by a factor of $-10$ expected for Magellanic Cloud clusters. The advantages of using $(J-K)_0$ over $(V-K)_0$ as a temperature indicator for late-type supergiant stars are (1) the simultaneous measurement of J and K removes any uncertainty in J-K due to stellar variability, (2) the greater accuracy of the J-K measurement compared to V-K, which requires a difference between two independent magnitudes to be taken, largely compensates for the steeper slope of the $T_e$ vs $(V-K)_0$ calibration, (3) the V magnitude can be sensitive to metal abundance variations, especially in cool stars where TiO bands are present, and so should be avoided in programs such as the present one where abundance variations possibly exist.
Frogel, Persson and Cohen (1981) have questioned both the importance of TiO blanketing in the V pass band in metal deficient cool stars and the use of (J-K) as a temperature indicator since they claim that it too may suffer from blanketing effects. While J-K is certainly not totally free of abundance-sensitive blanketing effects, we feel that it is likely to be a more reliable temperature indicator in metal-deficient cool stars than V-K. These problems will be discussed further in §IVb.

The major disadvantage in using (J-K) as a temperature indicator is that published J photometry by different authors are often on different, and sometimes unspecified, instrumental systems (e.g. Frogel et al. 1978, MHl) which must be transformed to a standard system before they can be compared. We adopt the Johnson system (Johnson et al. 1966) as the standard system and define a new calibration of the Johnson (J-K) vs $T_e$ from published effective temperature determinations.

Effective temperature determinations for late-type stars based on lunar occultation radius measurements (Ridgway et al. 1980) and model atmosphere flux distribution fitting (Kodaira et al. 1979) have been used to define the calibration. Both these works involve only giant stars, however it will be assumed in this paper that the same $T_e$ vs (J-K) calibration applies to both supergiant and giant stars. Since differences of the order of 200K exist between the Johnson (1966) calibration of galactic giant and supergiant effective temperatures with (J-K) in the range $3600K \leq T_e \leq 4600K$ (see Fig. 1), we recognize that the above assumption may result in our over-estimating the supergiant effective temperatures reported here. However, more recent lunar occultation data for a few M supergiants suggest that the M giant and M supergiant temperature scales may in fact not be too different. The
FIG. 1 - Adopted calibration of effective temperature with Johnson (J-K) colour (dashed line). The previous giant star calibrations of Johnson (1966) (crossed line) and Cohen et al. (dotted line) and the supergiant calibration of Johnson (1966) (solid line) are also shown. Open triangles represent data for supergiant stars.
Ridgway et al. (1980)  
Kodaira et al. (1979)  
Tsujii (1979)  
White (1980)  
Adopted Calibration
Table 6

Adopted Effective Temperature Calibration

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<th>$T_e (°K)$</th>
<th>$(J-K)_o$</th>
<th>$T_e (°K)$</th>
<th>$(J-K)_o$</th>
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positions of the M supergiants 119 Tau, α Ori and α Sco in Figure 1 (Te from White 1980; J-K from Lee 1970) demonstrate this point. In view of the limited number of supergiant effective temperature determinations available, we feel that the above assumption is the most reasonable that can be made at the present time.

Johnson J-K colours \((J-K)_J\) for the stars with effective temperatures determined by Kodaira et al. (1979) were obtained from the photometry and transformations to the Johnson system given in that paper. The Ridgway et al. (1980) photometry is not on a well defined system, being the mean of photometry on the Kitt Peak and Johnson instrumental systems. An empirical transformation of the Ridgway et al. (1980) photometry to the Johnson system (Johnson et al. 1966) of

\[
(J-K)_J = 0.97 (J-K)_R + 0.09, \quad 0.5 \leq (J-K)_R \leq 1.1
\]

was determined using data for the twelve stars in common between these two works plus \((J-K)_J\) colours for BS 6913 and BS 7150 transformed from Glass (1974) (Fig. 2). Reddening corrections for the Ridgway et al. (1980) stars were derived from the E(V-K) values suggested in Ridgway et al. (1980) and from a comparison of their \((J-K)_J\) colours with the intrinsic giant colours of Johnson (1966) and Lee (1970). These two values agreed to better than 0.05 mag in all cases. No reddening corrections have been applied to the Kodaira et al. data. The Kodaira et al. (1979) stars and the twenty Ridgway et al. (1980) stars with effective temperatures determined to better than 250K are plotted in Figure 1 along with some similar determinations from Tsuji (1978). The adopted calibration is shown as a dashed line in Figure 1 and is tabulated in Table 6. Effective temperatures for the program stars, derived from this calibration are given in Tables 7, 8 and 9.
FIG. 2 - Transformation adopted between J-K data on the system of Ridgway et al. (1980) and the Johnson (1965) system. The solid line represents the transformation. The dashed line corresponds to \((J-K)_J = (J-K)_R\).
$$(J - K)_J = 0.97 (J - K)_R + 0.09$$
FIG. 3 - Adopted calibration of bolometric correction to the K magnitude with Johnson (J-K) colour (dashed line).
Lee (1970) Supergiants
Johnson (1956) Supergiants
Cohen et al. (1978)
-- Adopted calibration

The (J-K) vs (B-K) diagram for one significant observational program is shown in Figure A6(1), along with the 30 bolometrically

The (J-K) vs (B-K) diagram for one significant observational program is shown in Figure A6(1), along with the 30 bolometrically

The (J-K) vs (B-K) diagram for one significant observational program is shown in Figure A6(1), along with the 30 bolometrically

The (J-K) vs (B-K) diagram for one significant observational program is shown in Figure A6(1), along with the 30 bolometrically
(e) **Bolometric Corrections**

Bolometric corrections to the absolute K magnitudes, $BC_K$, have also been determined from the $(J-K)_o$ colour. The calibration of these quantities has been obtained from the empirical determinations of Johnson (1966) and Lee (1970) for supergiant stars and from the theoretical calculations of Cohen *et al.* The adopted calibration is shown in Figure 3. Bolometric corrections and bolometric magnitudes for the program stars are presented in Tables 7, 8 and 9.

**IV. INFRARED PHOTOMETRY AS AN ABUNDANCE INDICATOR**

(a) **The $(J-H)_o$ vs $(H-K)_o$ Diagram**

In MHL we demonstrated the significant effect that infrared CN bands can have on the broad band infrared colours of late-type supergiant stars. The well known positive luminosity dependence of the CN band strength in late-type stars causes luminosity class Ia red supergiants to be displaced in the $(J-H)_o$ vs $(H-K)_o$ plane to bluer $(J-H)_o$ and redder $(H-K)_o$ colours. CN abundance deficiencies act in the opposite sense in that metal deficient red supergiants are predicted to be displaced to redder $(J-H)_o$ and bluer $(H-K)_o$ colours so that they move closer to the mean galactic luminosity class Ib line of Lee (1970). The clear separation in this sense between the 30 Doradus M supergiants studied in MHL and h and Χ Persei stars of the same luminosity in the $(J-H)_o$ vs $(H-K)_o$ plane was interpreted in that paper as a consequence of metal deficiency in the 30 Doradus stars.

The $(J-H)_o$ vs $(H-K)_o$ diagram for the Magellanic Cloud stars in the present study is shown in Figure 4(a), along with the 30 Doradus data from MHL. A similar diagram for the galactic cluster stars is plotted.
### Table 7
SMC Derived Data

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### Table 8
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Table 9

Galactic Derived Data

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in Figure 4(b). Data for red supergiants surrounding the h and X Persei clusters have been taken from Lee (1970) and have been corrected for the mean cluster reddening listed in Table 5. The distributions of stars in Figure 4(a) and Figure 4(b) are clearly different, with the sense of the separation between Magellanic Cloud and galactic stars being the same as found in MHL. We note that differences in the instrumental photometric systems, which as noted above can be appreciable, cannot be used to explain the observed separation in the present data because all but the h and X Persei stars have been measured with the same photometer. Similarly, uncertainties in the applied reddening corrections cannot be responsible since the separation is perpendicular to the direction of interstellar reddening in this plane.

An examination of Tables 7, 8 and 9 and the discussion to follow in §V (cf. Figure 8) shows that the luminosities of the Magellanic Cloud stars are comparable to, if not slightly greater than, the luminosities of the galactic cluster stars. We are therefore again in the situation found in MHL where Magellanic Cloud and galactic stars of the same luminosity fall in different regions of the (J-H) vs (H-K) plane, although we now have a more comprehensive sample of objects with which to define this separation. Interpreting the separation in the same way as has been done for the 30 Doradus stars, we see that the observed separation is strong evidence for CN abundance deficiencies in the Magellanic Cloud late-type supergiants of this study. From the close positional agreement of the LMC blue globular cluster stars and the 30 Doradus stars, the scale of the abundance deficiency in the present LMC sample is expected to be similar to that of the 30 Doradus stars, which were estimated in MHL to be deficient by a factor of ~3. The abundances
FIG. 4 - (J-H)_o vs (H-K)_o diagram for (a) Magellanic Cloud supergiants and (b) galactic cluster supergiants. The mean galactic G and K giant line (Frogel et al. 1978) and the mean galactic Ia and Ib M supergiant lines (Lee 1970) are shown for comparison. The arrows indicate the direction of interstellar reddening.
of stars in the SMC cluster NGC 330 are difficult to quantify from the data presented in Figure 4(a).

NGC 330 is the brightest and presumably one of the youngest SMC blue globular clusters. Its properties should therefore be comparable to the properties of the LMC clusters in this study. However, on the basis of their \((J-K)_0\) colours, it is apparent that the late-type supergiants in NGC 330 are nearly all hotter than the LMC supergiants studied. A similar result, that the optical colours of these stars are bluer than those of galactic late-type supergiants, was first noted by Arp (1959b). This difference in stellar effective temperature is reminiscent of the earlier spectral types found for SMC supergiants by Humphreys (1979b).

As has been suggested previously (Arp 1959b, Humphreys 1979b, Glass 1979), such temperature differences are probably due to a general deficiency of heavy elements in the SMC relative to the LMC and the Galaxy.

Except for NGC 330/B15, the broad band infrared and optical colours of the NGC 330 stars are consistent with them being of K spectral type. This temperature classification appears to be more consistent than the classification of -G5Ib assigned to a number of red supergiants from this cluster by Feast (1979) on the basis of their blue spectra. Thus the infrared colours presented here add further support to Feast's claim that metal abundance deficiencies are responsible for his comparatively early spectral type assignments. NGC 330/B15, which lies apart from the other stars in this cluster in Figure 4(a), has JHK colours that are possibly indicative of carbon star characteristics. However, a spectrum of NGC 330/B15 obtained on the Mt Stromlo 74-inch telescope failed to show any indication of carbon star features.
Figure 4(b) also provides evidence that the large width of the band occupied by M supergiants in the \((J-H)_o\) vs \((H-K)_o\) plane extends at least to K spectral type in the Galaxy. This possibility was first discussed by Glass (1979) in relation to the brightest late-type supergiants in the SMC and is in fact suggested by the theoretical broad band infrared colours computed in MH1. The locations of the three \(h\) and \(X\) Persei stars in Figure 4(b) at \((J-H)_o\) - 0.65 mag may possibly be due to an overestimation of their reddening corrections, however the other five cluster stars in the same region of Figure 4(b) are the K supergiants from NGC 2323 and NGC 6067 and, for this reason, their positions cannot be in error in the direction of interstellar reddening by a large amount (for a galactic K3 giant \((J-H)_o\) - 0.68 and \((H-K)_o\) - 0.12). The displacement of these stars from the mean galactic giant line (Frogel et al. 1978) suggests that galactic giants and supergiants may be distinguished in the \((J-H)_o\) vs \((H-K)_o\) plane to spectral types as early as - K2.

(b) The \((V-K)_o\) vs \((J-K)_o\) Diagram

The combined \((V-K)_o\) vs \((J-K)_o\) diagram for all clusters studied is shown in Figure 5. The \(h\) and \(X\) Persei stars effectively define the mean galactic line (Johnson 1966) in this plane and have not been replotted. Both the galactic and Magellanic Cloud stars follow the mean galactic line up to the point \((J-K, V-K)\) - (0.97, 3.6). Galactic globular cluster stars also occur largely in this colour range and follow the same relation. Beyond this point, which corresponds to an effective temperature of ~3800K, TiO absorption becomes important in the V pass band of galactic supergiants, causing both the mean galactic line and the observed colours of the galactic supergiants in our sample to deviate to redder \((V-K)_o\) colours. The Magellanic Cloud supergiants in Figure 5 do not deviate
FIG. 5 - \((V-K)_{\odot}\) vs \((J-K)_{\odot}\) diagram for Magellanic Cloud and galactic cluster stars. The mean galactic supergiant line (Johnson 1966) is also shown. The arrow indicates the direction of interstellar reddening.
NGC 330 (SMC)  
NGC 2100 (LMC)  
NGC 2004 (LMC)  
NGC 1850 (LMC)  
Galactic cluster
in this manner, but maintain the same linear relation defined by the warmer supergiants of both galaxies. Thus, for $(J-K)_o \geq 1.0 \text{ mag}$, the Magellanic Cloud stars have bluer $(V-K)_o$ colours than the galactic stars of the same effective temperature (as measured by their $(J-K)_o$ colours). The TiO bands in these Magellanic Cloud supergiants should therefore be weaker than in galactic supergiants of the same $(J-K)_o$ colour. This prediction could be easily tested spectroscopically.

Similar $V-K$, $J-K$ discrepancies have been found for Magellanic Cloud giants in intermediate-age globular clusters (Mould and Aaronson 1980) and galactic globular cluster giants (Frogel et al. 1981). Mould and Aaronson interpret the discrepancy in the same way as has been done here. However, Frogel et al. (1981) question this interpretation for the metal-deficient giant stars, preferring to interpret the discrepancy as due to the effects on $(J-K)_o$ of lower CN and CO blanketing in the $K$ pass band in the metal deficient stars. We believe that this latter interpretation is not valid for the supergiants discussed here and, by implication, is most probably not valid for the globular cluster giant stars. Our reasons for believing this are the following: (1) The discrepancy first appears at effective temperatures of $-3800K$ and increases monotonically towards lower temperatures. The TiO opacity has precisely these characteristics, whereas CN and CO blanketing should be apparent at higher temperatures. (The strength of the red CN bands in low gravity stars is predicted to peak at a temperature of $-4400K$ and to decrease rapidly towards cooler temperatures (see e.g., Lambert and Ries 1977)). (2) At $(V-K)_o = 4.5$, the displacement required to bring the galactic and Magellanic Cloud supergiant sequences in Figure 5 into agreement is $\Delta(V-K) = 0.4 \text{ mag}$ or $\Delta(J-K) = 0.1 \text{ mag}$ (the corresponding
numbers quoted by Frogel et al. (1981) for giants are \( \Delta(V-K) \sim 0.9 \) mag or \( \Delta(J-K) \sim 0.07 \) mag. A blanketing of \( \sim 0.4 \) mag at \( V \) in solar abundance M supergiants does not seem to us to be too unreasonable since \( B-V \) for supergiants changes by only \( 0.08 \) mag between \( M0 \) and \( M4 \) (Lee 1970) due to the effects of TiO blanketing (black-body \( B-V \) colours change by \( \sim 0.4 \) mag between the temperatures appropriate to these spectral types). Frogel et al. (1981) presented evidence that for solar abundance and metal deficient giants of the same \( (V-K) \) colour the blanketing effect due to TiO is insufficient to account for the observed \( V-K, J-K \) discrepancy in giants. If TiO blanketing is significant at \( V \) in the solar abundance stars their comparison may not be valid. (3) As will be shown in §IVc, the CO indices of the LMC supergiants differ from those of galactic supergiants of the same \( (J-K) \) colour by only \( \sim 0.04 \) mag. This number would be decreased if the comparison was made at constant \( (V-K) \). Thus the differential effect on \( K \) of CO blanketing in the galactic and LMC supergiants is \( \lesssim 0.01 \) mag (since the CO bands occupy \( -20\% \) of the \( K \) pass band; Cohen et al.). (4) Theoretical infrared colour calculations (MHl) suggest that while the effect of CN blanketing in M supergiants on the \( K \) magnitude may be important, the effect on the \( J-K \) colour is quite small (the differential blanketing effect due to CN between \( [\Delta/H] = 0.0 \) and \( -1.0 \) was predicted to be \( \lesssim 0.03 \) mag in MHl). Thus the combined effect of variations in the CN and CO blanketing on \( (J-K) \) in M supergiants is likely to be \( \lesssim 0.04 \) mag; much less than the \( 0.1 \) mag required to explain the \( V-K, J-K \) discrepancy.

Thus in our opinion, Figure 5 clearly demonstrates the dangers involved in using \( (V-K) \) as a temperature indicator in metal deficient stars when the temperature is low enough for TiO to be an important opacity source in the calibrating stars. In such a situation \( (V-K) \)
will indicate an erroneously high temperature which may in turn cause the abundance deficiency to be overlooked. In galactic globular clusters this situation is only encountered for the coolest giant branch stars and does not compromise in any way the work which has led to the recent revision of globular cluster metallicities. Further investigations of the TiO band strengths in Magellanic Cloud supergiants are warranted and will be the subject of a future paper in this series.

(c) CO Absorption Band Strengths

The 2.3 µm CO absorption band indices for the galactic and Magellanic Cloud stars are plotted in Figures 6(a) and (b), respectively, along with the mean galactic giant line (Frogel et al. 1978; solid line) and the domain of giants from the galactic globular cluster M71 (Frogel et al. 1979; shaded region). It is immediately apparent from Figure 6 that the supergiant CO bands are much stronger than in galactic giants. Thus no detailed comparison with giant stars is possible. The mean relation for the galactic supergiants in our sample has been drawn in Figures 6(a) and (b) as a heavy solid line. The dashed lines in Figures 6(a) and (b) schematically represent the best fit LMC and SMC loci with the same slopes as the corresponding sections of the mean galactic supergiant line.

The LMC supergiants on average lie -0.04 mag below the mean galactic supergiant line, while the SMC supergiants (from NGC 330) have larger CO deficiencies (-0.1 mag at constant (J-K)0). This result is consistent with the SMC supergiants being more metal deficient than the LMC stars. A theoretical investigation of CO band strengths in late-type supergiants is currently underway by one of us (P.J.M.), so a detailed discussion of the abundance anomalies responsible for these CO deficiencies will be postponed until this work is completed. Nevertheless, some preliminary
FIG. 6 - \((CO_0\) vs \((J-K)_0\) diagram for (a) the galactic cluster supergiants and, (b) the Magellanic Cloud cluster stars. The heavy solid line (labelled I) in each diagram indicates the locus of galactic supergiants in this plane. Dashed lines indicate the mean LMC and SMC lines in this plane. The mean galactic giant line (labelled III) and the domain of M71 giants are also shown. The arrows indicate the direction of interstellar reddening.
results from this theoretical study are shown in Figure 7 where theoretical CO indices on the Frogel et al. (1978) system are plotted for models with $T_e/\log g/[A/H] = 4000/0.0/0.0$, $4000/0.0/-0.5$, $4000/0.0/-1.0$ and $3600/0.0/0.0$, $3600/0.0/-0.5$, $3600/0.0/-1.0$ for a microturbulent velocity of 2.5 km/s and $^{12}C/^{13}C = 20$. Here $T_e$ is the effective temperature, $g$ is the surface gravity and we adopt the usual convention that $[A/H] = \log (A/H) - \log (A/H)_\odot$ where $A/H$ is the heavy element abundance relative to hydrogen.

The model atmospheres were obtained by interpolation and extrapolation on a grid of models formed from the Bell et al. (1976) grid supplemented with six $\log g = 0.0$ ($[A/H] = 0.0$ and $-0.5$) models provided by B. Gustafsson. Flux distributions through the 2 µm window for these models have been synthesized using CO and CN line lists provided by F. Querci and described in Querci, Querci and Tsuji (1972). The resulting spectra were then convolved with the MSO narrow band CO filter profiles, shifted in wavelength to the positions of the Frogel et al. (1978) filters, and a CO index formed from the resulting colour. The zero point was set by forcing the index computed in this way from an α Lyr infrared flux distribution ($F_\lambda \propto \lambda^{-3.94}$, Kurucz 1979) to equal zero. This zero-point gives a theoretical CO index of 0.19 mag for α Tau (4000/1.5/0.0), in good agreement with the observed value (0.18; transformed from Baldwin et al.). The procedure will be described in more detail in a future paper (McGregor 1981).

The microturbulence and $^{12}C/^{13}C$ ratio are essentially free parameters in the analysis. To obtain agreement between the solar abundance theoretical CO indices in Figure 7 and the mean galactic supergiant line defined above, the $^{12}C/^{13}C$ ratio was fixed at 20 and the microturbulent
FIG. 7 - (CO)$_0$ vs (J-K)$_0$ diagram for the M supergiants in the central region of the 30 Doradus complex from MH1. The solid lines labelled I and III, and dashed lines labelled LMC and SMC are as in Fig. 6. Theoretical CO indices for models with $T_e$/log g = 4000/0.0 and 3600/0.0 and [A/H] = 0.0 (filled squares), -0.5 (half filled squares), -1.0 (open squares) are also shown.
[A/H] = 0.0

[A/H] = -0.5

[A/H] = -1.0

LMC

III

M71

SMC

30 Doradus
velocity varied. The value of 2.5 km/s obtained from this procedure is quite reasonable. From Figure 7 we see that the galactic and LMC supergiant CO indices differ by the same amount that the theory predicts for an overall heavy metal deficiency of a factor of 3. This same abundance deficiency was indicated for CN from the broad band photometry and is consistent with expectations for the general metal deficiency in the LMC. However, it must be recognised that it is possible for a decoupling of the CNO and heavier element abundances to occur and the effects of this on the observed CO indices are still to be investigated.

With the improved galactic supergiant data presented in this paper we are now in a better position to comment on the CO indices of the M supergiants near 30 Doradus (MHJ). The tight sequence formed by the 30 Doradus M supergiants in the (CO) vs (J-K) plane (solid circles in Fig. 7) closely matches the relation found for the LMC blue globular cluster supergiants. Thus the data of the present paper confirm the result reported in MHJ that the 30 Doradus M supergiants have weaker CO bands than in galactic supergiants of the same temperature. Furthermore, the magnitude of the abundance deficiency responsible for this weakness is of the same order as that required to explain the broad band infrared colours of these stars.

V. EVOLUTIONARY STATUS OF THE LATE-TYPE SUPERGIANTS

Stars in the red supergiant region of the CMD can be in either of two possible evolutionary states, depending on their masses. Red supergiants with high mass (M/M_☉ ≥ 10) have non-degenerate carbon-burning cores (e.g., Lamb, Iben and Howard 1976; hereafter LIH), while intermediate mass red supergiants (3 ≤ M/M_☉ ≤ 9) on the asymptotic giant branch have
inert electron-degenerate carbon-oxygen cores and burn hydrogen and helium in shells (e.g., Becker and Iben 1979, 1980). In the following we describe the observed giant branch morphologies of the clusters studied in this paper and compare them with theoretical predictions for red supergiants in each mass domain.

(a) **Observed Giant Branch Morphologies**

Log $L$-$\log T_e$ diagrams based on our infrared photometry and that of other workers for a number of systems containing red supergiants are presented in Figure 8. The Magellanic Cloud and galactic data from the present paper are shown in Figures 8(a) - (e). The red supergiants in the galactic clusters h and X Persei are shown in Figure 8(f), the 30 Doradus data presented in MHl are plotted in Figure 8(g), and the brightest variable LMC and SMC late-type supergiants from Glass (1979) are shown in Figures 8(h) and (i), respectively. Schematic representations of these giant branches are shown in Figure 9. The luminosities and temperatures of the 30 Doradus stars have been recomputed using the bolometric corrections and effective temperature calibrations derived in §III. The new giant branch is not significantly different from the one shown in MHl. Infrared data for the h and X Persei stars have been taken from Johnson and Mendoza (1966) and their luminosities and effective temperatures derived in the same manner as for the other clusters using the adopted cluster parameters in Table 5. In evaluating Figure 8(f) it is important to bear in mind that the adopted h and X Persei distance modulus is uncertain and may have been under-estimated by up to -0.4 mag (cf. Johnson and Hiltner 1956, see also discussion in Crawford et al.).
FIG. 8 - $M_{\text{BOL}}$ vs log $T_e$ diagrams for the giant branch regions of
(a) the SMC cluster NGC 330, (b) the LMC clusters NGC 2004 and
NGC 1850, (c) the LMC cluster NGC 2100, (d) the older galactic
clusters NGC 6067 and NGC 2323, (e) the galactic clusters NGC
2439, 3293, 3766 and 4755, (f) h and ρ Persei, (g) the older
population in the vicinity of 30 Doradus, and (h) and (i) the
brightest late-type variable supergiants in the LMC and SMC,
respectively. The horizontal lines in each frame represent
the upper luminosity limit of intermediate mass stars on the
asymptotic giant branch (see text).
FIG. 9 - Schematic composite $M_{BOL}$ vs $\log T_e$ diagram for the systems shown in Fig. 8.
All systems shown in Figure 8 possess well defined, nearly vertical giant branches. Differences in luminosity and temperature between each giant branch can best be appreciated from Figure 9. The two LMC cluster giant branches lie close to each other in the log L-log $T_e$ plane, with the NGC 2004 giant branch being slightly hotter and extending to a luminosity -0.5 mag brighter than for NGC 2100. The most luminous star on the NGC 2004 giant branch is a VV Cephei binary (Feast, Thackeray and Wesselink 1960). The evolutionary consequences of its binary nature are unknown. The giant branch for the SMC cluster, NGC 330, is displaced to higher temperatures and lower luminosities than the LMC cluster giant branches. The end-main sequence mass of NGC 330 was estimated in §III(c) to be $13M_\odot$ whereas the estimates for NGC 2004 and NGC 2100 were $14M_\odot$. This difference is in the correct sense to explain the lower luminosity of the NGC 330 giant branch, but the errors in the mass determinations are such that the difference of $1M_\odot$ is probably not significant.

Comparison with the behaviour of galactic globular cluster stars of different metallicities on the first giant branch suggests that the higher temperatures of the NGC 330 stars are probably due to their lower metallicities. This same suggestion was made in §IV(a). The galactic open cluster giant branches in Figure 8(e) and the h and X Persei giant branch all lie in good agreement with the LMC blue globular cluster giant branches. NGC 6067 (and BD-08°1699 in NGC 2323) has the hottest and lowest luminosity giant branch of the systems considered. This should not be surprising (since NGC 6067 contains K supergiants) and is indicative of NGC 6067 (and NGC 2323) being older than the other galactic clusters studied. The 30 Doradus giant branch (Fig. 8(g)) is cooler than any of the other LMC or galactic giant branches shown and covers the same luminosity range found for NGC 2004. Instead of being
restricted to a narrow range in temperature, the 30 Doradus supergiants
occupy a band in the log L-log $T_e$ plane -0.1 dex wide in temperature.
In this respect the 30 Doradus giant branch resembles that of NGC 2100,
although the width of the NGC 2100 giant branch is not as great. NGC
2100 is situated close to the 30 Doradus complex on the sky in a region
of considerable interstellar extinction so both systems may be subject
to non-uniform reddenings. The width of the giant branch in NGC 2100,
however, cannot be explained in that way because a variation in $E(B-V)$
of -0.5 mag would be required and it is immediately apparent from the
width of the main sequence in NGC 2100 (Robertson 1974a) that such a
reddening variation across the cluster does not exist. The tight
correlation of CO index with $(J-K)_o$ for the 30 Doradus M supergiants
(MHl and Fig. 7 of this paper) argues against the existence of large,
unaccounted for reddening variations in these stars. The brightest
LMC and SMC variable stars present a different giant branch morphology
(Figs. 8(h) and (i)). These giant branches are based on inhomogeneous
supergiant samples which undoubtedly contain stars covering a large mass
range. They extend to higher luminosities than any of the other giant
branches considered and, unlike the other giant branches (except possibly
NGC 2100), tend towards higher temperatures at higher luminosities.
It can be seen from Figure 9 that, as with NGC 330, the SMC variable
supergiants lie at higher temperatures and lower luminosities than
equivalent LMC supergiants. The same interpretation in terms of lower
metallicity comes to mind again here.

(b) Comparison with Theoretical Evolutionary Tracks

Evolutionary tracks for high mass and intermediate mass stars are
shown in Figure 10. The sections of the tracks where stars are most
likely to be found are shown as solid lines; sections where evolution
FIG. 10 - Evolutionary tracks for high and intermediate mass stars. The 15 $M_\odot$ tracks is from Lamb, Iben and Howard (1976), the 12 $M_\odot$ track is from Robertson (1972) and the 7 $M_\odot$ track is from Becker (1981) and Becker and Iben (1979). The outline of observed giant branches from Fig. 9 is also shown.
In more rapid rotation, some stars on the H-R diagram may generate over-cooling and escape the observed upper limits in the luminosity of stars on the main sequence. This is supported by the observation that very rapid rotation can generate core collapse and prevent the thermal timescale of the star from being consumed.

The AGB limit for AGB stars is based on the following assumptions:

- The initial mass of the AGB star is 10 M☉.
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- The initial mass of the AGB star is 10 M☉.

The results of these assumptions are: the AGB limit for AGB stars is based on the following assumptions:

- The initial mass of the AGB star is 10 M☉.
- The initial mass of the AGB star is 10 M☉.
- The initial mass of the AGB star is 10 M☉.
- The initial mass of the AGB star is 10 M☉.

These results suggest that in a significant spread in the initial mass of the AGB stars, a significant spread in the mass of the AGB stars may be due to the initial mass. This may be associated with a significant spread in the initial mass of the AGB stars.
is more rapid are shown as broken lines. Intermediate mass stars on the AGB can evolve to comparatively high luminosities for their masses. The upper limit to the luminosity of stars on the AGB is set by the restriction that their degenerate core mass cannot exceed the Chandrasekhar limit (\( \sim 1.4 M_\odot \)). From the stellar mass dependent core mass-luminosity relation of Iben (1977), with a representative total stellar mass of \( 7M_\odot \), the AGB luminosity limit is predicted to be \( M_{BOL} \sim -7.3 \) mag. This luminosity limit for AGB stars is marked on each frame in Figure 8 and in Figures 9 and 10. From Figure 10 we see that in the luminosity range of the Magellanic Cloud giant branches discussed above, both high mass and intermediate mass AGB stars are predicted to occur.

On the basis of the blue globular cluster end-main sequence masses (Table 4), all the Magellanic Cloud blue globular cluster supergiants should be high mass stars (\( M/M_\odot \sim 14 \)). Late-type supergiants of this mass are predicted to have luminosities in the range found for the blue globular cluster supergiants, however the carbon core burning phase of their evolution should be confined to a narrow range in luminosity. Thus, if the blue globular cluster supergiants are high mass stars, the large range of -2 mag in the luminosity of the cluster giant branch stars must be due to the existence of a significant spread in their masses (\( 12 \leq M/M_\odot \leq 16 \)) which must be associated with a significant spread in the formation times of the stars within each cluster. From the evolutionary tracks of Robertson (1972) we estimate that the 2 mag luminosity spread corresponds to an age spread for the supergiants within each cluster of \( -8 \times 10^6 \) yrs. This requirement is not unreasonable. In fact, it compares well with the value of \( -10^7 \) found by Robertson (1974b) for the stellar age spread in slightly older LMC blue globular clusters from a consideration of the observed luminosity of their blue giants.
The blue globular cluster giant branch morphologies are also consistent with their supergiants being intermediate mass stars. The close agreement of the upper luminosity limit for the blue globular cluster giant branches with the AGB limit (especially if the VV Cephei binary in NGC 2004 is omitted) and the narrow, nearly vertical giant branch morphologies are simply explained in an intermediate mass interpretation. However, significant post-main sequence mass loss ($\dot{M} \gtrsim 10^{-6} M_\odot \text{ yr}^{-1}$) would be required to reduce the cluster end-main sequence masses to the intermediate mass range and, even if this was achieved, it is not clear that a degenerate stellar core would form. Consequently, we will not consider this possibility further. We note that if the end-main sequence masses of Robertson (1973) were adopted, the Magellanic Cloud cluster red supergiants would be underluminous by -1 mag compared with predictions based on these high masses and significant post-main sequence mass loss would have been required in either explanation of their giant branch morphologies.

The situation for the galactic clusters NGC 2323 and NGC 6067 (Fig. 8(d)) is more straightforward since neither their end-main sequence masses ($\sim 5M_\odot$) nor their giant branch luminosities permit them to contain high mass stars. The supergiants in these clusters are expected to be in the helium burning phase of their evolution, on the first giant branch. The galactic cluster stars in Figure 8(e) can be simply interpreted as high mass stars (with masses as shown in Table 5), however, the h and X Persei giant branch displays the same spread in luminosity as discussed above for the blue globular clusters. Age variations among the h and X Persei stars have previously been reported by Wildey (1964) and Schild (1967) in agreement with our interpretation of the blue globular cluster giant branches.
No satisfactory explanation of the cooler 30 Doradus giant branch is suggested from the evolutionary tracks in Figure 10. Comparison with the 15\(M_\odot\), solar abundance track (LIH) suggests that the 30 Doradus supergiants are too cool to be high mass stars. However, the temperature at which core carbon burning is predicted to occur may depend on the helium burning rates adopted (Brunish 1981, private communication). The temperatures of the 30 Doradus supergiants appear to be consistent with them being 7-9 \(M_\odot\) stars at the top of the AGB. However, as discussed in MH1, the luminosities of the brightest stars on the 30 Doradus giant branch exceed the AGB limit. This and other arguments were presented in MH1 which led us to favor an interpretation of the 30 Doradus supergiants as high mass stars. Further evolutionary tracks at 15\(M_\odot\) for \(Z = 0.02\) (solar) and \(Z = 0.01\) (Brunish 1981) show the effects of small changes in metallicity on the evolution of red supergiants to be small but in the sense of lower metallicity being associated with higher temperatures. Thus the cooler temperatures of the 30 Doradus supergiants are not likely to be due to metallicity effects. The same general dependence of giant branch temperature on metallicity was found for AGB stars by Becker and Iben (1979). We can find no reason based on the data presented in this paper for revising our earlier suggestion that the 30 Doradus supergiants are high mass stars. Thus, as with the blue globular cluster supergiants, the luminosity spread of \(-1\) mag on the 30 Doradus giant branch most likely corresponds to a spread in the formation times of the older red population in 30 Doradus of \(-4 \times 10^6\) yrs. This time spread should be compared with a mean age of \(-1.2 \times 10^7\) yrs for the 30 Doradus red population, if the mean stellar mass is \(-15M_\odot\).
The many bright LMC and SMC variables in Figures 8(h) and (i) lying well above the AGB limit are clearly high mass stars and should therefore have carbon burning cores. The carbon core burning zone in the log L-log $T_e$ plane is predicted to run approximately parallel to the core helium burning and core hydrogen burning (main sequence) zones (LIH). Thus the locus of high mass red supergiants in Figures 8(h) and (i), which as pointed out above tend towards higher temperatures at higher luminosities, may empirically define the normal core carbon burning zones in the log L-log $T_e$ plane for LMC and SMC abundances, respectively.

In summary we have interpreted the giant branch morphologies of each system in the manner which is most consistent with the cluster end-main sequence masses and with recent theoretical calculations for the evolution of massive stars. It was possible to interpret all stars either as high mass stars in the core carbon burning phase of their evolution or as intermediate mass core helium burning first giant branch stars. In no case did we interpret a supergiant as being on the asymptotic giant branch. This should perhaps not be too unexpected since the end-main sequence masses of most clusters considered are in the high mass range. Further observational data for Magellanic Cloud blue globular clusters with end-main sequence masses in the intermediate mass range will be required to identify stars on the asymptotic giant branch.
VI. CONCLUSIONS

Evidence for metal deficiency has been found in the infrared properties of a number of Magellanic Cloud late-type supergiants in blue globular clusters. The Magellanic Cloud supergiants have redder (J-K)$_o$ colours and bluer (H-K)$_o$ colours than galactic supergiants of the same luminosity. This separation of the Magellanic Cloud and galactic stars in the (J-H)$_o$ vs (H-K)$_o$ plane is in the same sense and is of the same magnitude as found earlier for the M supergiants in the central region of the 30 Doradus complex. On the basis of the theoretical broad band infrared colours presented in that paper, we associate the cause of the separation with CN abundance deficiencies in the Magellanic Cloud stars.

The (V-K)$_o$ colour has been shown to be an unreliable temperature indicator in these metal deficient late-type supergiants. In galactic supergiants of the same temperature TiO is likely to be an important opacity source. It is predicted that the TiO band strengths in the Magellanic Cloud stars are weaker than in galactic supergiant stars of the same temperature.

The CO bands in the LMC supergiants are weaker than in galactic supergiants of the same temperature by -0.04 mag. The 30 Doradus M supergiants are displaced from the galactic supergiant line in the (CO)$_o$ vs (J-K)$_o$ plane by the same amount as found for the LMC blue globular cluster stars. Preliminary theoretical calculations show that an overall metal abundance deficiency of a factor of -3 is sufficient to explain the observed separation. The SMC stars show larger CO deficiencies (-0.1 mag) relative to the galactic stars.
The blue globular cluster supergiants generally have masses consistent with their cluster end-main sequence masses. The range in luminosity of stars on the cluster giant branches requires that the blue globular cluster stars formed over a time span of $10^7$ yrs. These clusters are currently $2 \times 10^7$ yrs old. The 30 Doradus giant branch is cooler than the other cluster giant branches and extends over a considerable range in temperature (-0.1 dex). This appears to be a real effect, not due to uncertainties in the adopted reddening corrections. The giant branches of the brightest variable LMC and SMC supergiants probably define the core carbon burning zones in the $M_{\text{bol}}$ vs $T_e$ plane for these two galaxies.

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CHAPTER 4

CO BAND SYNTHESIS AND THE INTERPRETATION OF BAND STRENGTHS IN MAGELLANIC CLOUD SUPERGIANTS

P.J. McGregor

ABSTRACT

Theoretical 2.3 µm first-overtone CO indices are presented for a range of supergiant model atmospheres. The CO index is shown to be very sensitive to microturbulent velocity. The larger CO indices observed for galactic supergiants relative to giants can be understood if the mean microturbulent velocity in supergiants is only \(-1 \text{ km sec}^{-1}\) larger than in giants. The weaker CO indices for Large Magellanic Cloud supergiants, relative to similar stars in the Galaxy, are consistent with an overall metal abundance deficiency of a factor of \(-3\) in the LMC. The weaker CO indices for supergiants in the Small Magellanic Cloud cluster NGC 330 cannot be easily understood by an overall abundance deficiency in these stars of a factor of 10 (characteristic of the SMC). Either \([\text{A/H}]=-1.5\) or \([\text{A/H}]=-1.0\) and \([\text{C/A}]=-0.5\) is suggested to explain the small CO indices for these SMC stars. Much lower microturbulent velocities in the NGC 330 supergiants compared with the other supergiants may also be responsible.
I. INTRODUCTION

To date a considerable amount of observational data in the form of indices for the 2.3 µm first-overtone CO bands in late-type giants and supergiants has been accumulated (e.g., Cohen, Frogel and Persson 1978, Frogel, Persson and Cohen 1979, Persson et al. 1980, Frogel, Persson and Cohen 1981, McGregor and Hyland 1981a, b; hereafter MHI and MH2, respectively). Only a few, very limited attempts have so far been made to compare this data with theoretical predictions, and by so doing obtain quantitative CO abundance estimates (Bell, Dickens and Gustafsson 1979, Bell and Dickens 1980, MH2).

In MHI and MH2 infrared photometric data were presented for a number of late-type supergiants in the Magellanic Clouds and the Galaxy. In MHI we demonstrated that the observed differences between the broad band infrared (JHK) colours of galactic and Large Magellanic Cloud (LMC) supergiants of the same luminosity could be interpreted as due to CN abundance deficiencies of a factor of approximately 3 in the LMC stars. In MH2 it was shown that the CO indices for the LMC supergiants are weaker than for galactic supergiants of the same (J-K)₀ colour by -0.04 mag. This shift is small in comparison with the observed CO indices (-0.3 mag) and a theoretical analysis is required to determine whether the implied CO deficiency is consistent with the CN deficiency suggested from broad band data. CO indices for supergiants in the Small Magellanic Cloud (SMC) blue globular cluster NGC 330 were found to be -0.1 mag smaller than for galactic supergiants of the same (J-K)₀ colour.

1 MHI = Chapter 2, MH2 = Chapter 3.
In this paper we describe spectrum synthesis calculations in the 2.0 - 2.5 μm region (the K window) (§II) and present a grid of theoretical CO indices that can be used in the analysis of observational supergiant CO data. This grid is used here (§III) to interpret the observed separation between galactic and Magellanic Cloud late-type supergiants in the (CO) vs (J-K) plane. Preliminary results of this analysis were presented in MH2 where it was shown that the LMC supergiant CO indices were consistent with an overall heavy element deficiency of a factor of -3. This result and a similar comparison for the NGC 330 supergiants are now studied in more detail and the possibility of decoupling between the CNO and heavier element abundances investigated.

II. THE SPECTRUM SYNTHESIS TECHNIQUE

Synthetic spectra with a wavelength step size of 0.25 Å have been computed for the region 2.0 - 2.5 μm using a variation of the Mount Stromlo spectrum synthesis program. The program is based on the ATLAS5 model atmosphere code (Kurucz 1970) and was written by P. Cottrell (Cottrell and Norris 1978). Major changes have since been made to the method of handling spectral line input data and to the internal manipulation of molecular number densities, however the basic physics is essentially unchanged from that described by Cottrell and Norris. The model atmospheres were obtained by interpolation, and in some cases extrapolation, on the grid of model atmospheres of Bell et al. (1976), supplemented by six log g = 0.0 (T_e = 4500, 4250, 4000K; [A/H] = 0.0, -0.5) models kindly provided by B. Gustafsson. Extrapolation outside this grid to lower temperatures (e.g., 3600K) may not be strictly
justified because the TiO line opacity, which increases in importance towards lower temperatures and has a strong effect on the atmospheric structure, was not included in the original model calculations.

The adopted logarithmic solar carbon, nitrogen and oxygen abundances are 8.55, 7.93, 8.77, respectively, relative to \( \log \varepsilon_H = 12.00 \) (Kurucz 1970). The species included in the molecular equilibrium calculations and their adopted dissociation energies have been listed in an Appendix to Chapter 2 and will not be repeated here. Standard ATLAS5 continuous opacity routines were used. The line list includes lines of CO, CN and atomic species. Wavelengths, excitation potentials and line strengths for the CO and CN lines were taken from a magnetic tape file kindly supplied by F. Querci (Querci, Querci and Tsuji 1972). The Querci et al. line strength parameter, \( S_0 \), was converted to a gf-value using the relation

\[
gf = \frac{m_e c^2}{4\pi e^2} \frac{\mu_{\text{mol}}}{N_A} S_0
\]

where \( \mu_{\text{mol}} \) is the molecular weight of the species, \( N_A \) is Avogadro's number and other symbols have their usual meanings. Similar data for the atomic lines were taken from the lists of Kurucz and Peytremann (1975). The final line list contained -6700 lines. The line mass absorption coefficient in frequency units was computed from the standard equation

\[
\kappa_\nu = \frac{\pi e^2}{mc} \frac{N_{\text{mol}}}{\rho} \frac{\exp(-X_e/kT) \exp(-h\nu/kT)}{Q_{\text{mol}}} [1-\exp(-\frac{h\nu}{kT})] \phi(\nu)
\]

where \( N_{\text{mol}} \) is the total number density of the species, \( X_e \) is the line excitation potential, \( Q_{\text{mol}} \) is the total partition function [from Tatum (1966) for CO and CN] and \( \phi(\nu) \) is the line profile. Other symbols have
their usual meanings. The line profile is assumed to be a Voigt function with damping from radiation, Doppler, and collisional broadening. Molecular collisional broadening was approximated in the manner of Querci, Querci and Kunde (Eq. 12; 1971).

(a) **Observational Comparison**

Before proceeding to form CO indices from these synthetic spectra it is worthwhile demonstrating that the synthetic spectra do give a good representation of the CO spectra in real stars. Observed and theoretical 2 µm spectra for α Tau are compared in Figure 1. The observed spectrum has a nominal resolution of 32 Å and is taken from Frogel (1971). The theoretical spectrum was computed in the manner described above for parameters appropriate to α Tau and has been convolved with a Gaussian filter to match the observational resolution. Bell and Gustafsson (1978) adopt the parameters $T_e/\log g/[A/H]/v_{TURB} = 4000/1.5/0.0/2$ for α Tau. ($T_e$ is the effective temperature, $g$ is the surface gravity, $v_{TURB}$ is the microturbulent velocity and we use the usual notation for the heavy element abundance that $[A/H] = \log(A/H)_x - \log(A/H)_o$). However, these authors suggest that the effective temperature of α Tau may be as low as 3750K. Based on published infrared photometry (Lee 1970) and the empirical $T_e$ vs $(J-K)_o$ calibration defined in MH2 we estimate $T_e = 3830 \pm 150K$. Tsuji (1978) obtained $T_e = 4000 \pm 150K$ for α Tau by fitting the shape of the stellar flux distribution. Consequently, we have adopted the parameters $T_e/\log g/[A/H]/v_{TURB} = 3900/1.5/0.0/2$ for α Tau. The theoretical spectrum was computed with $^{12}C/^{13}C = 12$ (Tomkin and Lambert 1974). The agreement in Figure 1 is sufficiently good (especially considering the uncertainties in the adopted atmospheric parameters) that no adjustment of the molecular oscillator strengths is justified.
FIG. 1 - Observed 2 µm spectrum of a Tau (solid line) is compared with theoretical spectrum for model parameters 3900/1.5/0.0/2 (dotted line). $^{12}\text{CO}$ and $^{13}\text{CO}$ band heads are indicated.
(b) **CO Indices**

Observational CO indices are usually defined from narrow band photometry by forming a colour between a band region (2.3 - 2.4 µm) and a continuum region (2.2 µm) (Baldwin, Frogel and Persson 1973), Frogel et al. 1978, MH2). The theoretical CO indices reported in this paper are intended to be on the system of Frogel et al. (1978). Since the filter transmission curves for this system have not been published, we have formed CO indices by convolving the synthetic spectra with the Mount Stromlo Observatory (MSO) narrow band filter transmission curves, with the central wavelength of the band filter shifted to 2.36 µm (the central wavelength of the Frogel et al. (1978) filter), and forming a CO index in the same way that an observational index is formed. The continuum filters in the MSO and Frogel et al. (1978) systems are centred at the same wavelengths. The transmission properties of the MSO narrow band filters at their operating temperature are tabulated in the Appendix. A detector response function proportional to wavelength was also included in the calculations. Bandwidth differences do exist between the filters in the Frogel et al. (1978) and MSO systems (the most serious being for the band filters where Δλ_F = 0.08 µm and Δλ_{MSO} = 0.10 µm) and these may introduce small (≤ 0.01 mag) systematic errors in the theoretical indices. The zero-point of the Frogel et al. (1978) system is set by forcing the CO index of α Lyr to be zero. The zero-point of the theoretical system was set by requiring that the index calculated from the infrared flux distribution of the Kurucz (1979) α Lyr model (F_λ ∝ λ^{-3.94}) is zero. From our experience at measuring CO indices from circular variable filter spectra of late-type supergiants, ratioed to the spectrum of the A6IV star, BS2015, we estimate that the uncertainty in the theoretical zero-point introduced by
neglecting BY absorption in α Lyr in the continuum filter is likely to be <0.01 mag. Thus the theoretical CO indices are on a system that is as close as we are able to achieve to the Frogel et al. (1978) system.

In principle the accuracy with which we have imitated the Frogel et al. (1978) system could be gauged by comparing theoretical and observed CO indices for other stars with accurately determined atmospheric parameters. However, CO indices on the Frogel et al. (1978) system are not available in the literature for any stars that we feel have sufficiently well determined atmospheric parameters for this purpose. It has therefore been necessary to resort to the CO indices of Baldwin et al. and use the empirical transformation between the Baldwin et al. and Frogel et al. (1978) systems given in MH2 to make this comparison. Transformed theoretical CO indices and observed CO indices on the Baldwin et al. systems for α Tau and α Boo are compared in Table 1. Atmospheric parameters and CNO abundances for α Boo are taken from Lambert and Ries (1977). The agreement is considered to be satisfactory when allowance is made for the considerable uncertainty in the empirical transformations.

Table 1
Comparison of Observed and Theoretical CO Indices on the Baldwin et al. System

<table>
<thead>
<tr>
<th>Star</th>
<th>T_e (K)</th>
<th>log g</th>
<th>[A/H]</th>
<th>V_TURB</th>
<th>(^{12}\text{C}/^{13}\text{C})</th>
<th>CO_B THEORY</th>
<th>CO_B OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>α Tau</td>
<td>3900</td>
<td>1.50</td>
<td>0.0</td>
<td>2</td>
<td>12</td>
<td>0.111</td>
<td>0.100 ± 0.003</td>
</tr>
<tr>
<td>α Boo</td>
<td>4250</td>
<td>1.70</td>
<td>-0.6</td>
<td>2.4</td>
<td>7.2</td>
<td>0.087</td>
<td>0.079 ± 0.001</td>
</tr>
</tbody>
</table>
The major uncertainty in the theoretical supergiant CO indices is that associated with the model atmospheres. The uncertainty in extrapolating the Bell et al. (1976) grid to lower temperatures due to the increasing importance of low temperature opacity sources was noted above. Uncertainties due to the breakdown of the classical model atmosphere assumptions are also expected in the coolest, low gravity models (see, e.g., Schmid-Burgk, Scholz and Wehrse 1981 for a discussion of sphericity effects and Thompson 1973 for a discussion of the importance of non-LTE effects for the CO vibration-rotation level populations). Chromospheric heating may also be important in the outer layers of real supergiants (Linsky and Haisch 1979).

In all cases discussed in this paper, the J-K colour associated with a given theoretical CO index has simply been taken to be the \((J-K)_0\) colour corresponding to the model effective temperature in the \(T_e\) vs \((J-K)_0\) calibration described in MH2. (Dereddened empirical colours and CO indices are indicated by subscript zeroes throughout this paper). Thus for \(T_e = 4500, 4000, 3800\) and \(3600\)K we set \(J-K = 0.71, 0.87, 1.00\) and \(1.11\) mag, respectively. Since the \(T_e\) vs \((J-K)_0\) calibration was based only on galactic giants, the positions of our metal deficient theoretical points in the \((CO)_0\) vs \((J-K)_0\) diagram could be in error in \((J-K)_0\) by a small amount which will be estimated below. Overcoming this problem requires the detailed computation of accurate broad band infrared colours for the Bell et al. (1976) model atmospheres. That task is beyond the scope of this paper.

An upper limit to the probable error in \((J-K)_0\) due to metallicity differences can be obtained by considering only the effect on \(K\) of extreme changes in the CO band strength. Using the crude approximation
ΔK - 0.20 ΔCO (Cohen et al.), a 0.20 mag change in the CO index would produce only a 0.04 mag change in K, and hence at most a 0.04 mag change in J-K. The typical uncertainty in J-K should be considerably less than this value. Thus the results of this investigation are not likely to be affected by the uncertainty in J-K due to the dependence of J-K on metallicity.

(c) Theoretical Comparison

Bell and Dickens (1980) have computed theoretical CO indices for comparison with galactic globular cluster giant data. CO indices computed by these authors are compared with indices computed with our code for the same atmospheric parameters and CNO abundances in Table 2.

<table>
<thead>
<tr>
<th>[C/A] [O/A]</th>
<th>4000/0.75/-1.5</th>
<th>4500/1.5/-1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>Bell and Dickens</td>
</tr>
<tr>
<td>0.0 +0.3</td>
<td>.117</td>
<td>.130</td>
</tr>
<tr>
<td>0.0 0.0</td>
<td>.112</td>
<td>.126</td>
</tr>
<tr>
<td>-0.5 -0.5</td>
<td>.062</td>
<td>.082</td>
</tr>
<tr>
<td>-1.0 0.0</td>
<td>.032</td>
<td>.051</td>
</tr>
</tbody>
</table>
The sensitivities of both sets of CO indices to changes in abundance are similar but the CO indices of Bell and Dickens (1980) are systematically larger than those computed here by, on average, 0.02 mag. Systematic differences of this order will not affect the results of the differential analysis used in §III. However, the origin of the discrepancy with the present calculations remains unclear. Inadequacies in the adopted filter characteristics or errors in the zero-points used in either our calculations or those of Bell and Dickens (1980) may be responsible.

III. QUANTITATIVE ABUNDANCES FROM SUPERGIANT CO INDICES

The CO data for galactic and Magellanic Cloud late-type supergiants from MH1 and MH2 are shown schematically in Figure 2. The solid lines marked I and III are the mean galactic supergiant and giant lines, respectively. The dashed lines represent the mean LMC and NGC 330 (SMC) supergiant relations. The samples on which the supergiant lines are based were generally selected to contain evolved supergiants from young galactic open clusters and Magellanic Cloud blue globular clusters with end-main sequence masses in the range 8-15 $M_\odot$. Thus in an evolutionary sense the supergiant samples contain closely comparable stars from each galaxy. NGC 330, the brightest SMC blue globular cluster, was the only SMC cluster studied in MH2. The labelled tick marks along each line indicate mean values for the surface gravity ($\log g$) of stars at different positions along each line. Surface gravities for the individual supergiants were derived in MH1 and MH2. Mean surface gravities along the giant line were estimated from mean solar neighbourhood luminosities (Tinsley and Gunn 1976) and a typical solar neighbourhood giant mass of 2 $M_\odot$. In the following we attempt to interpret this diagram.
FIG. 2 - Mean lines in the $(CO)_0$ vs $(J-K)_0$ plane for galactic supergiants (labelled I), galactic giants (labelled III), LMC supergiants and NGC 330 (SMC) supergiants. The tick marks along each line indicate mean surface gravities $(\log g)$ for stars at those positions.
When determining quantitative abundances from a comparison of empirical and theoretical supergiant CO indices we are immediately confronted by an oversupply of free parameters that are not constrained by the present low resolution data. We therefore choose to fix the $^{12}\text{C}/^{13}\text{C}$ ratio at 20 (see Hinkle, Lambert and Snell 1976, and references therein) and determine a mean microturbulent velocity for galactic supergiants by forcing the solar abundance, $\log g = 0.0$ models to intersect the mean galactic supergiant line in the $(\text{CO})_0$ vs $(J-K)_0$ plane at the position appropriate to galactic supergiants of that surface gravity. We then make the assumption, at least initially, that the mean microturbulent velocities for our comparable galactic and Magellanic Cloud supergiant samples are the same. Figure 3 shows the theoretical CO indices for $\log g = 0.0$, $T_e = 4000K$ and $3600K$, $^{12}\text{C}/^{13}\text{C} = 20$ (solid symbols) and $^{12}\text{C}/^{13}\text{C} = 10$ (open symbols) for a range of microturbulent velocities ($1.0 - 3.5 \text{ km sec}^{-1}$) overlayed on the galactic supergiant and giant lines from Figure 2. (All theoretical CO indices discussed in this paper are tabulated in the Appendix). Several points can be noted from Figure 3. First, the CO index is very sensitive to microturbulent velocity (cf., Frogel 1971, Manduca, Bell and Gustafsson 1981). This is clearly due to the CO band absorption being dominated by saturated lines. The tight relation in the $(\text{CO})_0$ vs $(J-K)_0$ plane found in MH1 for the 30 Doradus supergiants is therefore strong evidence that the microturbulent velocities in these stars are extremely uniform. This fact supports our use of one mean microturbulent velocity for all the late-type supergiants studied. Second, the implied supergiant microturbulent velocities are not large (cf., Tsuji 1976 where a
FIG. 3 - Theoretical CO index versus J-K diagram for $\log g = 0.0$, solar abundance models with $T_e = 4000$, 3600K and $^{12}\text{C}/^{13}\text{C} = 20$ (solid lines) and 10 (broken lines) for a range of microturbulent velocities from 1.0 to 3.5 km sec$^{-1}$. The mean galactic supergiant and giant lines from Figure 2 are also plotted.
microturbulent velocity of 12 km sec$^{-1}$ is used to model α Ori). In fact, for $^{12}$C/$^{13}$C ratios of order 20, mean microturbulent velocities in excess of -3.5 km sec$^{-1}$ are excluded. Third, the dependence of the CO index on the $^{12}$C/$^{13}$C ratios is small compared with the dependence on microturbulence. Thus, the results of this paper are not significantly affected by our choice of the $^{12}$C/$^{13}$C ratio. Since we assume $^{12}$C/$^{13}$C = 20, the galactic supergiant line is best fitted using a mean supergiant microturbulent velocity $v_{\text{TURB}} = 2.5$ km sec$^{-1}$; we adopt this value for all supergiants studied. This value is similar to the values obtained spectroscopically in the 8000 Å region by Luck (1978) for the microturbulent velocities in galactic G and K supergiants. In Figure 4 we plot the observed galactic supergiant line and a theoretical line for models with $v_{\text{TURB}} = 2.5$ km sec$^{-1}$ and atmospheric parameters appropriate to galactic supergiants. The excellent agreement between the empirical and predicted supergiant lines further strengthens our case for defining a mean microturbulent velocity for each supergiant sample. For galactic giants, we find that a mean microturbulent velocity of 1.6 km sec$^{-1}$ gives the best agreement between theory and observation. This value is in good agreement with the microturbulent velocities found by Lambert and Ries (1977) for galactic field giants. The larger CO indices for supergiants compared to giants are a result of both the lower supergiant surface gravities (see Figure 5 below) and the (slightly) higher supergiant microturbulent velocities. Both these effects are required to explain the observed difference in CO index.
FIG. 4 - Theoretical CO vs J-K diagram for models appropriate to galactic supergiants (open symbols). Model points are labelled with $T_e/\log g$ and were computed for $v_{\text{TURB}} = 2.5 \text{ km sec}^{-1}$. The empirical galactic supergiant locus (heavy line) from Figure 2 is shown for comparison.
Theoretical supergiant CO indices for a range of abundances are presented in Figure 5. CO indices for solar abundance models are shown in Figure 5(a). Figures 5(b), (c) and (d) correspond to all elements heavier than helium being deficient by factors of 3, 10 and 30, respectively, relative to the Sun. CO indices for effective temperatures of 4500, 4000, 3800 and 3600K are plotted. Different symbols correspond to different surface gravities. Solid lines connect points of equal surface gravity but different effective temperature. The mean galactic, LMC and NGC 330 (SMC) supergiant lines from Figure 2 are also shown. The goodness of fit in these diagrams is set by the accuracy with which the theoretical lines intersect the observed lines at the correct surface gravity. Surface gravities along the galactic supergiant line are marked in Figure 5(a). As was seen in Figure 4, the theoretical solar abundance lines in Figure 5(a), computed with \( v_{\text{TURB}} = 2.5 \text{ km sec}^{-1} \), fit these marked points extremely well over the full length of the supergiant line.

(a) LMC Abundances

Surface gravities along the mean LMC line are marked in Figure 5(b) and (c). As was noted in MH2, reasonable agreement with the LMC mean line is obtained with \([A/H]\) equal to or slightly greater than -0.5. This value is consistent with other abundance results for the LMC (see, e.g., van den Bergh 1975) and is in agreement with the approximate abundance suggested for these stars from broad band infrared data (MH1, MH2).

Nevertheless, departures from the solar CNO/A abundance ratios and differences in the mean microturbulent velocities of the LMC and galactic supergiant samples may influence the observed CO indices and the importance of these effects must also be investigated. Theoretical CO indices for
FIG. 5 - Theoretical supergiant CO index vs J-K diagrams for 
(a) solar abundance, (b) [A/H] = -0.5, (c) [A/H] = -1.0 and 
(d) [A/H] = -1.5. Theoretical indices are plotted for \( T_e = 4500, 4000, 3800 \) and 3600K. Surface gravities are indicated 
by \( \log g = 0.0 (\square), 1.0 (\triangle), 2.0 (O) \) and 3.0 (X).

Galactic, LMC and SMC mean supergiant lines from Figure 2 
are also shown. Numbers along these lines refer to mean 
stellar surface gravities at that position. All theoretical 
supergiant CO indices are computed with \( v_{TURB} = 2.5 \) km sec\(^{-1}\).
logg = 0.0 and \([A/H] = -0.5\) with non-solar C/A and N/A abundances are shown in Figure 6 as open symbols. Decreasing the carbon abundance decreases the CO number density directly. Increasing the nitrogen abundance increases the CN number density which increases the CN blanketing in the CO index continuum filter (cf., Frogel et al. 1981), also resulting in a reduced CO index. The theoretical indices presented in Figure 6 demonstrate that both effects cause significant changes to supergiant CO indices, although the greater sensitivity is clearly to changes in carbon abundance. In oxygen-rich stars, such as those in the present study, the CO number density is controlled by the atmospheric carbon abundance. Thus changing the atmospheric oxygen abundance has only a small effect on the CO index (see, e.g., Table 2). If the heavy element abundance in the LMC supergiants is \([A/H] = -0.5\) and if our assumption that the mean microturbulent velocities of galactic and LMC supergiants do not differ is valid, then the fit to the mean LMC line (Figure 5(b)) and the sensitivity of that fit to the C/A ratio suggest that the mean carbon abundance for the LMC supergiants lies in the range \(0.0 \leq [C/A] \leq +0.2\). The most probable result is that \([A/H] = -0.5\) and \([C/A] = 0.0\) in the LMC supergiants. The scatter of individual LMC supergiants about the mean line (MH2) is most likely due to observational errors, although variations in the individual LMC CNO/A ratios and (small) variations in the individual microturbulent velocities may also contribute.

If, however, the mean microturbulent velocity for the LMC supergiant sample is actually lower than for the galactic supergiant sample by \(-0.5\) km sec\(^{-1}\) agreement could also be obtained between theory and observation using solar heavy element abundances (Fig. 3). The abundances obtained in this way are inconsistent with other LMC abundance
FIG. 6 - Theoretical supergiant CO index vs J-K diagram showing the dependence of CO index on N/A and C/A ratios for log g = 0.0 at the heavy element abundance characteristic of the LMC ([A/H] = -0.5). Solid symbols have solar N/A and C/A ratios.
results and with the results from broad band infrared data for these stars (as quoted above) and for these reasons we do not consider this possibility further.

(b) NGC 330 Abundances

Surface gravities along the mean SMC line are marked in Figure 5(b), (c) and (d). The heavy element abundance in the SMC is usually considered to lie in the range \(-0.6 > \frac{[A/H]}{1} > -1.0\) (van den Bergh 1975, Smith 1980). However, no agreement is obtained in Figure 5(c) between the theoretical CO indices computed with \(\frac{[A/H]}{1} = -1.0\) and the mean line for stars in the SMC cluster NGC 330. This result contrasts with the good agreement with the LMC data found above for a heavy element deficiency typical of the LMC. Fair agreement with the NGC 330 mean line is obtained if all heavy elements are deficient by a factor of -30 (i.e., \(\frac{[A/H]}{1} = -1.5\); Fig. 5(d)). (The \(\log g = 0.0\) CO indices in Figure 5(d) (open symbols) are merely linear extrapolations of the \(\log g = 1.0\) and 2.0 results since no \(\log g = 0.0\), \(\frac{[A/H]}{1} = -1.5\) models were available in our grid). However, deviations from the solar CNO/A ratios and microturbulent velocity differences between the NGC 330 and galactic supergiants are other possible explanations of the small CO indices measured for the NGC 330 supergiants.

The sensitivity of the CO index to changes in the C/A and N/A ratios for \(\frac{[A/H]}{1} = -1.0\) is shown in Figure 7. If we assume that the heavy element abundance in the SMC is \(\frac{[A/H]}{1} = -1.0\) reasonable agreement with the mean NGC 330 line can be obtained with \(\frac{C/A}{1} = -0.5\). No realistic increase in the N/A ratio is sufficient on its own to explain the observations. Alternatively, further calculations show that if the
FIG. 7 - Theoretical supergiant CO index vs J-K diagrams showing dependence of CO index on N/A (left) and C/A (right) ratio at heavy element abundances characteristic of the SMC. Symbols for different surface gravities are as in Figure 5. Solid symbols have solar N/A and C/A ratios, open symbols have abundances as indicated. The mean SMC supergiant line is shown in each case.
The observed $[A/H]=-1.0$ for $T = 4000$ K is consistent with the general trend of lower $[A/H]$ values as the temperature decreases. This trend is associated with the influence of turbulence on the spectroscopic observations. The close agreement between the $[A/H]$ values for the different temperatures indicates the reliability of the measurements. The fact that the mean $[A/H]$ for the entire sample is close to the solar value supports the idea of an internal origin for these variations, which could be related to the overall turbulence in the stellar atmospheres.
mean microturbulent velocity in the NGC 330 supergiants is only \(-1.5 \text{ km sec}^{-1}\), the observed NGC 330 supergiant line should also be reproduced with \([A/H] = -1.0\) (for \(T_e = 4000\text{K}, \log g = 0.0, [A/H] = -1.0\) and \(\nu_{\text{TURB}} = 1.5, 1.0\) and \(0.5 \text{ km sec}^{-1}\) we obtain theoretical CO indices of 0.146, 0.125, 0.110 mag, respectively). This velocity is similar to the mean microturbulent velocity of \(1.6 \text{ km sec}^{-1}\) we derived for galactic giant stars. Unfortunately, the present low resolution CO data are not adequate for us to exclude the possibility that the small CO indices measured for the NGC 330 supergiants are due to a large difference in the mean microturbulent velocities of the NGC 330 and galactic supergiant samples. Much higher resolution would be required to uniquely determine the microturbulent velocities in these stars at the depth of formation of the CO features.

Thus the present calculations suggest that either the overall heavy element abundance in the NGC 330 supergiants could be as low as \([A/H] = -1.5 \pm 0.2\) or their heavy element abundance may be typical of the SMC \([A/H] = -1.0\) and either \([C/A] = -0.5 \pm 0.2\) or they have microturbulent velocities as low as we require to fit galactic field giant CO indices (i.e., \(-1.5 \text{ km sec}^{-1}\)). In the first two alternatives we are led to the result that \([C/H]\) may be as low as \(-1.5\) in the evolved supergiants in NGC 330. Since the NGC 330 stars have the luminosities and masses of supergiants and because we are unaware of any strong evidence for a correlation between metallicity and microturbulent velocity in supergiants (cf., Gray 1978), we feel that it is unlikely that the mean microturbulent velocity for the NGC 330 stars is as low as in giant stars. This possibility will not be discussed further.
IV. DISCUSSION AND SUMMARY

In the foregoing it has been demonstrated that the chemical abundances in the late-type supergiants in the SMC blue globular cluster, NGC 330, may deviate from the mean abundances expected for typical young Population I objects in that galaxy. Janes and Carney (1977, 1980) have briefly described observations of the DDO 63842 and δCN indices in four late-type supergiants in NGC 330 which they interpret as suggesting that [Fe/H] ≲ -1.3 in this cluster, in agreement with the above result. This interesting possibility for the SMC stars contrasts with the situation for the LMC supergiants which were found to have mean CO indices in agreement with those predicted for abundances typical of the LMC.

CNO abundance anomalies in late-type stars are generally attributed either to primordial abundance differences or to chemical mixing in the atmospheres of evolved stars. The mixing of nuclear processed material to the stellar surface is predicted to occur in moderately massive late-type stars. Stellar evolution calculations for a 15 Mₖ solar abundance model (Lamb, Iben and Howard 1976) have predicted surface composition changes during the red supergiant phase of [C/A] = -0.18 and [N/A] = +0.52 when the convective envelope dredges up material previously processed during hydrogen burning on the main sequence. Although the surface composition changes caused by convective mixing may be greater in metal deficient stars of this mass (cf., Becker and Iben 1979), the solar abundance result suggests that a carbon depletion of [C/A] = -0.5 is unlikely to result from convective mixing alone. Nevertheless, if convective mixing had contributed to a carbon depletion in the NGC 330 supergiants, the carbon depletion would be accompanied by a significant nitrogen enhancement. Unfortunately, we have no way of independently estimating both the carbon and nitrogen abundances in the NGC 330 stars from the present data. The result of Janes and Carney
(1977) from DDO photometry suggests that the CN abundance in the NGC 330 supergiants is not anomalous. However, DDO photometry is not likely to be very sensitive to the CN band strength when \([A/H] = -1.3\). If convective mixing alone was responsible for a carbon depletion in the NGC 330 stars, we might also expect to have found evidence for a similar degree of mixing in the LMC supergiants; this was not found.

Meridional circulation in red supergiants that had high rotational velocities on the main sequence has been suggested as the additional mixing mechanism required to explain the very low \(^{12}\text{C}/^{13}\text{C}\) ratios (i.e., <20) found in some galactic supergiants (Tomkin, Luck and Lambert 1976, Luck 1977). The fact that NGC 330 contains a large number of Be stars on the main sequence has led Feast (1972) to suggest that most main sequence stars in NGC 330 are fast rotators (since the Be phenomenon is generally associated with rotational instability). Thus the late-type supergiants in NGC 330 are excellent candidates for meridional circulation mixing processes. This phenomenon may provide a satisfactory explanation for the carbon depletion suggested for the NGC 330 supergiants.

Alternatively, if the carbon abundance in the NGC 330 supergiants has remained coupled to the heavy element abundance (i.e., \([\text{C/A}] = 0.0\) we may be confronted with the potentially even more interesting result that the heavy element abundance in this very young (-10^7 yrs) SMC cluster could be as low as \([\text{A/H}] = -1.5\). This result would imply that gas clouds with abundances considerably lower than is normal for the interstellar medium in the SMC have been swept up by, or have survived in, the SMC until very recently. Further comment on such a far-reaching possibility is not justified until firm evidence can be offered in support of this low abundance.
In summary, analysis of the 2.3 µm CO indices for Magellanic Cloud late-type supergiants has shown that the mean CO indices for the LMC supergiants are consistent with the mean young Population I abundances in that galaxy. If the NGC 330 and galactic supergiant samples have similar mean microturbulent velocities, the chemical abundances in the late-type supergiants in the SMC blue globular cluster NGC 330 are probably unlike typical Population I SMC abundances. Either $[\text{A/H}] = -1.5$ and $[\text{C/A}] = 0.0$ or $[\text{A/H}] = -1.0$ and $[\text{C/A}] = -0.5$ have been suggested to explain the observed CO indices for the NGC 330 supergiants. The latter situation would be consistent with the changes in surface composition expected from the mixing of C-N processed material to the stellar surface if it is accompanied by a nitrogen enhancement. Conditions in the NGC 330 supergiants are likely to be favourable for meridional circulation mixing.

Further investigation of the NGC 330 supergiants to better determine their heavy element abundances, possibly using atomic line spectra, and their carbon abundances, possibly through investigations of the G band, are needed to clarify the chemical compositions in these stars. Feast's (1979) classification of seven late-type supergiants from NGC 330 as -G5Ib (although B-V = 1.3 - 1.6), and his comments that the hydrogen lines appeared strong and the blue CN bands appeared weak, may indicate that studies such as those suggested above in the blue spectral region would prove rewarding. A determination of the $^{12}\text{C}/^{13}\text{C}$ ratio in the NGC 330 supergiants would also be valuable in assessing the importance of mixing processes in these stars. It may soon be possible to obtain 2 µm spectra of the isotopic bands of CO in these stars at sufficient resolution for this ratio to be estimated using the new infrared grating spectrometer recently commissioned at Mount Stromlo Observatory.
ACKNOWLEDGEMENTS

The author is grateful to Dr. B. Gustafsson for providing unpublished model atmospheres, to Dr. F. Querci for allowing access to his molecular line list data and to Drs. A.R. Hyland and J.E. Norris for commenting on the manuscript. Modifications to the Mt. Stromlo spectrum synthesis program were made in collaboration with Mr. K. Ratnatunga. The calculations were performed on the UNIVAC 1100/82 computer operated by the Computer Services Centre of the Australian National University. The author acknowledges the support of an Australian Commonwealth Postgraduate Research Award.
## A P P E N D I X

### Table A1

Transmission Properties of MSO Narrowband CO Filters at 77K

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<th>(a) Continuum Filter</th>
<th>(b) Band Filter</th>
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Table A2 (a)

CO Indices for $^{12}\text{C}/^{13}\text{C} = 20$, log $g = 0.0$

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<th>$T_e$ (K)</th>
<th>$v_{\text{TURB}}$ (km sec$^{-1}$)</th>
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</thead>
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Table A2 (b)

CO Indices for $^{12}\text{C}/^{13}\text{C} = 10$, log $g = 0.0$

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</thead>
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<td>.408</td>
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Table A3

Theoretical Galactic Supergiant Locus

$^{12}\text{C}/^{13}\text{C} = 20$ \hspace{1cm} $v_{\text{TURB}} = 2.5$ km sec$^{-1}$

<table>
<thead>
<tr>
<th>$T_e$ (K)</th>
<th>log $g$</th>
<th>$[\Lambda/\text{H}]$</th>
<th>CO</th>
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<td>0.0</td>
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<td>4650</td>
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Table A4

CO Indices for $^{12}C/^{13}C = 20$, $v_{\text{TURB}} = 2.5$ km sec$^{-1}$

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<th>$[\text{A/H}] = -0.5$</th>
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<td>3.0</td>
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<td>.070 .103 .122 .145</td>
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<th>$[\text{A/H}] = -1.5$</th>
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<tr>
<td>3.0</td>
<td>.043 .074 .091 .112</td>
<td>– – – –</td>
</tr>
</tbody>
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Table A5

CO Indices for log g = 0.0, [A/H] = -0.5

\((v_{\text{TURB}} = 2.5, ^{12}\text{C}/^{13}\text{C} = 20)\)

<table>
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<tr>
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<th>4000</th>
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<th>3600</th>
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<td>.253</td>
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<tr>
<td>[C/A]=-0.5</td>
<td>.107</td>
<td>.175</td>
<td>.196</td>
<td>.216</td>
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</table>

Table A6 (a)

CO Indices for [A/H] = -1.0, [N/A] = +1.0

\((v_{\text{TURB}} = 2.5, ^{12}\text{C}/^{13}\text{C} = 2.0)\)

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Table A6 (b)

CO Indices for [A/H] = -1.0, [C/A] = -0.5

\((v_{\text{TURB}} = 2.5, ^{12}\text{C}/^{13}\text{C} = 20)\)

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SYNTHETIC SPECTRUM ANALYSIS OF TITANIUM-OXIDE BAND STRENGTHS IN MAGELLANIC CLOUD SUPERGIANTS

P.J. McGregor

ABSTRACT

TiO band strength data are presented for a number of Magellanic Cloud and galactic late-type supergiants for which published near-infrared data are available. At a given (J-K)_0 colour (i.e., effective temperature), the Magellanic Cloud supergiants have weaker TiO bands than the galactic supergiants.

A synthetic spectrum approach is used to analyse these observed TiO band strengths. Reasonable agreement with the observed TiO band strengths for galactic stars is obtained using the model atmospheres of Johnson, Bernat and Krupp (1980) which include TiO opacity in their computation. An analysis based on these models shows that the TiO band strengths in the LMC supergiants are, on average, consistent with the factor of 3 metal abundance deficiency suggested previously for these stars. An upper limit of [A/H] \leq -0.5 for the heavy element abundance in the NGC 330 (SMC) supergiants is indicated from the weakness of their TiO bands.
I. INTRODUCTION

In this series of papers the observational properties of a sample of late-type supergiants in young Magellanic Cloud blue globular clusters have been investigated with the intention of determining chemical abundances in these stars. Evidence for CN and CO abundance deficiencies have been presented (McGregor and Hyland 1981b; hereafter MH2) and the CO data interpreted using a spectrum synthesis approach (McGregor 1981). Abundance deficiencies consistent with those expected for young Population I objects in the Large Magellanic Cloud (LMC) have been indicated for the LMC supergiants. A more complicated picture has evolved for the supergiants in the Small Magellanic Cloud (SMC) cluster, NGC 330, which suggests that either carbon may be depleted relative to other heavy elements in the atmospheres of these stars or their heavy element abundances may be significantly lower than expected for young Population I objects in the SMC.

An investigation of the TiO band strengths in the blue globular cluster supergiants is of importance in this study because the TiO abundance is related to the heavy element abundance through the titanium component of the molecule and may therefore allow us to place constraints on the heavy element abundances in the Magellanic Cloud supergiants. However, the TiO abundance also depends directly on the oxygen abundance and indirectly on the carbon abundance through the CO molecular equilibrium. The effects of variations in these abundances on the TiO band strengths should also be considered in our analysis.

1 MH2 ≡ Chapter 3

Although the measurement of TiO band strengths in Magellanic Cloud supergiants presents no major practical problems, the theoretical analysis of this data using model atmosphere techniques is difficult because the TiO band strength is very sensitive to the temperature structure in the outer layers of the atmosphere. Model atmosphere temperatures in these layers are notoriously uncertain due to the usually adopted practices of neglecting non-LTE, sphericity, chromospheric and other effects which may be important in the outer layers. Because the TiO bands are so sensitive to the temperature structure, the problem can actually be inverted and the TiO band strengths, at least for the galactic stars, used to determine the accuracy of the model atmospheres, and hence also determine the accuracy of a band strength analysis based on these models. This is the approach that will be taken here.

The TiO bands in Magellanic Cloud supergiants are known to be weaker, on average, than in galactic supergiants. Spectroscopic studies of late-type supergiants in the Magellanic Clouds have shown that the spectral type distributions for these stars shift progressively towards earlier spectral types as we pass from the Galaxy to the LMC and to the SMC (Humphreys 1979b). Since the TiO band strength is the major temperature indicator in the classification of late-type supergiant spectra, this result indicates that, on average, the SMC supergiants have the weakest TiO bands. This weakness is most likely due either directly to TiO abundance deficiencies in the Magellanic Cloud stars or to temperature differences between the Magellanic Cloud and galactic supergiants, possibly caused by the indirect effects of abundance deficiencies in the Magellanic Cloud stars on their evolution. In the latter case the SMC supergiants would be hotter, on average, than the galactic supergiants,
however their TiO bands would not necessarily be anomalously weak for their temperatures. Clearly, a knowledge of both the TiO band strengths and effective temperatures (e.g., from infrared photometry) of a sample of Magellanic Cloud supergiants is required to distinguish between these possibilities.

In this paper, TiO band strength data are presented (in §II) for most of the Magellanic Cloud supergiants for which we have previously obtained infrared photometry (MH2, McGregor and Hyland 1981a; hereafter MH1). In MH2 it was predicted on the basis of their positions in the \((V-K)_0\) vs \((J-K)_0\) plane that our LMC stars should have weaker TiO bands than galactic supergiants of the same \((J-K)_0\) colour. The new data allows this prediction to be tested directly and, in combination with the effective temperatures already derived from our infrared photometry, allows us to investigate the cause of the generally earlier spectral types found for Magellanic Cloud supergiants (§III). The band strength data is then used in a spectrum synthesis analysis of the \(\Delta v = 0\) bands of the TiO \(Y\) and \(Y'\) electronic systems. Predictions based on the model atmospheres of Bell et al. (1976) and Johnson, Bernat and Krupp (1980) are compared with the observations in §IV and quantitative estimates of the TiO abundances in the Magellanic Cloud stars based on the models of Johnson et al. are made in §V. Our conclusions are summarized in §VI.

II. OBSERVATIONS

Spectra between 4800Å and 7800Å have been obtained with the Mount Stromlo Observatory 74" telescope using the Boller and Chivens cassegrain spectrograph and the two element 1D Photon Counting Array (PCA; Stapinski, Rodgers and Ellis 1979) on the nights of 1979 November 28 and 29 for 17

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3 MH1 = Chapter 2.
late-type supergiants in the LMC blue globular clusters NGC 2100, NGC 2004 and NGC 1850 and the SMC blue globular cluster NGC 330 (MH2). A 300 l/mm grating blazed to 5000 Å was used in the first order, giving a dispersion of ~280 Å/mm at the detector. The slit width was set to 250 µm, corresponding to a nominal resolution of ~10 Å.

On the same nights comparison spectra of the M supergiant in the galactic open cluster NGC 2439 (MH2) and of a sample of galactic field giants which have been assigned spectral types on the system of Wing (1971, 1978) were obtained using the same instrument. The galactic giants were chosen to cover the spectral type range between K5 and M8. Similar observations of the M supergiants in the galactic open clusters NGC 3293 and NGC 3766 (MH2) were also obtained in 1981 January using the same instrument. It was necessary to attenuate the starlight for the galactic star observations using a set of calibrated neutral density filters. The effects of these filters have been removed in the reduction procedure. Apart from this division, the reductions of the galactic and Magellanic Cloud spectra were identical, following standard procedures of sky subtraction, flat fielding and conversion to absolute fluxes based on the calibration star V Ma 2 (Oke 1974). Infrared photometry for the Magellanic Cloud and galactic supergiants have been presented previously (MH2).

Similar spectra of the M supergiants in the central region of the 30 Doradus complex of the LMC (MH1), obtained on the Anglo-Australian Telescope using the Image Dissector Scanner in 1976 November by D.A. Allen and A.R. Hyland, have been used to measure TiO band strengths in the 30 Doradus stars. Infrared photometry for the 30 Doradus supergiants was presented in MH1.
III. EVIDENCE FOR TiO WEAKNESS IN MAGELLANIC CLOUD SUPERGIANTS

(a) Qualitative Discussion of the Spectra

Several important qualitative points can be demonstrated from a cursory examination of the selected TiO spectra in Figure 1. The prominent TiO features in the spectral region shown are identified in Figure 1(d). CD $-31^\circ$ 4916 (Fig. 1(a)) is the galactic supergiant of spectral type M3Iab-Ib in the open cluster NGC 2439 (Morgan and Keenan 1973). Figure 1(b) and (c) show the spectra of two LMC supergiants with similar (J-K)$_0$ colours to that of CD $-31^\circ$ 4916. (Dereddened colours are indicated by a subscript zero). Thus all three stars have essentially the same effective temperature (~3600K) (MH2). It is immediately apparent from Figure 1(a) - (c) that these LMC stars have weaker TiO bands than the galactic supergiant with the same effective temperature and (J-K)$_0$ colour; thus confirming the prediction to this effect made in MH2 based on broad band photometry. The generality of this result will be demonstrated in §III(b). This result strongly suggests that direct abundance effects are responsible for the band strength differences between these stars because evolutionary temperature effects are excluded. Thus a similar origin to the general spectroscopic differences found by Humphreys (1979b) between her Magellanic Cloud and galactic supergiant samples seems likely.

Humphreys (1979b) also noted that the Magellanic Cloud supergiant spectra she classified did not appear peculiar and showed no strong evidence for metal deficiency. At first sight this result is in conflict with the comparisons of Figures 1(a) - (c) made above. Actually, the two LMC supergiant spectra in Figures 1(b) and (c) (which are both very similar) match the TiO spectrum of the hotter galactic M0.7III giant
FIG. 1 - Selected TiO spectra of Magellanic Cloud and galactic supergiants: (a) is the galactic M3Iab-Ib supergiant CD -31° 4916 in the cluster NGC 2439, (b), (c), (d), and (f) are the LMC blue globular cluster supergiants NGC 2004/D14, NGC 2100/W44, NGC 2100/C8 and NGC 1850/C20, respectively, (e) is the 30 Doradus M supergiant Dor IR 18, and (g) is the SMC blue globular cluster supergiant NGC 330/B10. TiO bands and pseudo-continuum points are marked in (d). CD -31° 4916, NGC 2004/D14, and NGC 2100/W44 have essentially the same effective temperature. The TiO bands in these LMC supergiants are clearly weaker than in CD -31° 4916. NGC 2100/C8 is cooler than CD -31° 4916 but its TiO spectrum is similar to that of CD -31° 4916. No TiO bands are apparent in the spectrum of the SMC supergiant NGC 330/B10.
Dor IR18  \[ T_e = 3000K \] \[ (J-K)_0 = 1.30 \]

NGC 1850/C20  \[ T_e = 3750K \] \[ (J-K)_0 = -1.03 \]

NGC 330/B10  \[ T_e = 3900K \] \[ (J-K)_0 = 0.94 \]

- NaID
- Hα

Wavelength (Å)
BS2639 (spectral type from Wing 1978; spectrum not shown here) very well. If no additional temperature information had been available the two LMC supergiants would undoubtedly have been assigned spectral types significantly earlier than CD -31° 4916 and no spectral peculiarities would have been discerned. (Spectral types on the MK system are actually based on blue spectra not red spectra as we use here, however this distinction is not likely to affect the point being made.) The same result can be illustrated by comparing Figures 1(a) and (d). Figure 1(d) shows the spectrum of the LMC cluster supergiant NGC 2100/C8. An effective temperature of ~3450K has been estimated for this star from its (J-K)₀ colour (MH2), yet its TiO spectrum does not differ significantly from that of CD -31° 4916 which is 0.05 mag bluer in (J-K)₀ (~150K cooler in effective temperature). These comparisons demonstrate that the TiO spectra of Magellanic Cloud supergiants are generally well matched by the spectra of hotter galactic supergiants.

For this reason, many of the Magellanic Cloud supergiants with apparently normal spectra classified by Humphreys (1979a, b) are expected to have significantly cooler effective temperatures than their assigned spectral types suggest. If present, such temperature differences should be apparent in the infrared colours of Humphreys' supergiants. Infrared photometry is available for a small number of these stars (Glass 1979, MH2) and allows us to assign mean (J-K)₀ colours to each spectral type for Humphreys' LMC and SMC supergiant samples (Table 1). The mean colours for galactic supergiants are taken from Lee (1970). Comparison of these colours for each galaxy shows that, at a given spectral type, Humphreys' Magellanic Cloud supergiants are indeed redder in (J-K)₀ (i.e., cooler) than galactic supergiants. Furthermore, for supergiants of the same (J-K)₀ colour (i.e., effective temperature), Humphreys' LMC supergiants
have been assigned spectral types -1 spectral class earlier, and her SMC
supergiants have been assigned spectral types -2.5 spectral classes
earlier than would be assigned to galactic supergiants. Since these
shifts are of the same order as the mean spectral type shifts found by
Humphreys (1979b), no temperature differences are required between
Humphreys' galactic and Magellanic Cloud supergiant samples to explain
the observed mean spectral type shifts. Thus direct abundance difference
effects are probably responsible for the observed shifts.

Figure 1(e) and (f) show the spectra of the supergiants Dor IR 18,
from the 30 Doradus region, and NGC 1850/C20, respectively. Both these
spectra show strong Hα absorption due to inexact cancellation of the
nebula emission in their vicinities. NGC 1850/C20 is hotter than the
other LMC supergiants in Figure 1 and has correspondingly weaker TiO
bands. The SMC supergiant NGC 330/B10 (Fig. 1(g)) is typical of the
supergiants observed in this cluster. Its effective temperature (~3900K)
is hotter than for the LMC stars in Figure 1. No TiO bands are apparent
from a qualitative inspection of this spectrum.
(b) Quantitative Band Strengths

Quantitative band strengths for the $\Delta v = 0$ bands of the TiO $\gamma$ system ($A^3\Pi - X^3\Delta$) at $-7100\AA$ and TiO $\gamma'$ system ($B^3\Pi - X^3\Delta$) at $-6200\AA$ (see Fig. 1(d)) have been determined by measuring pseudo-equivalent widths for the features. By this we mean that we have measured equivalent widths of the features relative to the apparent continuum, rather than relative to the true continuum. This procedure is necessary because it is impossible to define the true continuum level in heavily blanketed M supergiants. For each band two pseudo-continuum points are defined which experience lower blanketing than neighbouring regions in heavily blanketed spectra. A linear pseudo-continuum is then drawn between these points. The pseudo-equivalent width of the feature, $E^*$, is defined to be the total equivalent width in Ångstroms under this pseudo-continuum and between the two continuum points. Thus,

$$E^* = \int_{\lambda_1}^{\lambda_2} \frac{F_\lambda}{F_\lambda^C} d\lambda$$

where $F_\lambda$ is the stellar flux and $F_\lambda^C$ is the adopted continuum flux.

For the $\gamma$ bands $\lambda_1 = 7050\AA$ and $\lambda_2 = 7550\AA$. For the $\gamma'$ bands $\lambda_1 = 6145\AA$ and $\lambda_2 = 6535\AA$. It must be stressed that these pseudo-equivalent widths are not true equivalent widths and do not necessarily increase in proportion to the TiO line strengths because the adopted pseudo-continuum also varies with the level of absorption.

The adopted pseudo-continuum points for both bands are indicated in Figure 1(d) by arrows and the procedures for measuring $E^*_{71}$ and $E^*_{62}$, the pseudo-equivalent widths of the $\gamma$ and $\gamma'$ bands, respectively, are depicted schematically in Figure 2(a) and (b), respectively. The measured
FIG. 2 - Schematic illustrations of the procedure for measuring pseudo-equivalent widths for the TiO bands (see text). For the $\gamma(\Delta v=0)$ bands (a), the equivalent width, $E_{71}^*$, is measured between pseudo-continuum points at $\lambda_1 = 7050\AA$ and $\lambda_2 = 7550\AA$. For the $\gamma'(\Delta v=0)$ bands (b), the equivalent width, $E_{62}^*$, is measured between pseudo-continuum points at $\lambda_1 = 6145\AA$ and $\lambda_2 = 6535\AA$. 
The equivalent widths for the supergiant and planetary nebulosae are listed in Table 3 and 4. These values are based on the calibration of Table 2. The planetary nebulae data are presented in Table 5. Additionally, stellar types have been estimated using spectral classification. The results of this classification are also listed in Table 6.

The equivalent widths for the supergiant and planetary nebulae are presented in Figure 3 for the F band and in Figure 4 for the G band. These spectra represent the integrated area under the curve, which is also listed in the table as 

\[ E^*_G \]

The uncertainties in the supergiant \( E^*_G \) values in general are 3-4%.
equivalent widths for the Magellanic Cloud and galactic supergiants are presented in Tables 2 and 3, respectively, along with \((J-K)_o\) colours and effective temperatures from MH1 and MH2 (effective temperatures for the 30 Doradus stars are based on the calibration with \((J-K)_o\) given in MH2). The galactic giant data are presented in Table 4. For the galactic giants, it has not been possible to measure \((J-K)_o\) colours directly (because many of these stars are too bright for the MSO infrared system) so effective temperatures for these stars have been estimated from their measured Wing spectral types using the calibration of Ridgway et al. (1980) and \((J-K)_o\) colours for these stars (denoted \(<J-K>_o\) in Table 4) have been estimated from the \(T_e\) vs \((J-K)_o\) calibration described in MH2 which is also based on the Ridgway et al. (1980) data. The uncertainty in the tabulated equivalent widths is largely due to the uncertainty in the placement of the pseudo-continuum points and is estimated to be \(\pm 10\lambda\). The uncertainty in the supergiant \((J-K)_o\) colours is in general \(\pm 0.03\) mag and in the effective temperatures is \(\pm 150\)K.

The equivalent width measurements of all stars in the sample are plotted versus \((J-K)_o\) in Figure 3 for the \(\gamma\) bands and in Figures 4 for the \(\gamma'\) bands. Open symbols represent Magellanic Cloud stars and filled symbols represent galactic stars in each case. For both bands, the galactic giant stars (filled circles) follow well defined sequences in the \(E^*\) vs \((J-K)_o\) diagrams. The best eye fit to these sequences are shown as solid lines. The galactic supergiants (filled triangles), although fewer in number, also appear to follow well defined sequences in the \(E^*\) vs \((J-K)_o\) diagrams (dashed lines). This is, of course, to be expected since the \(E^*\) vs \((J-K)_o\) diagrams, in essence, relate MK spectral type to effective temperature.
### Table 2

Magellanic Cloud TiO Band Strengths

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<th></th>
<th>(J-K)</th>
<th>T&lt;sub&gt;e&lt;/sub&gt; (°K)</th>
<th>E&lt;sub&gt;62&lt;/sub&gt; (Å)</th>
<th>E&lt;sub&gt;71&lt;/sub&gt; (Å)</th>
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### Table 3

Galactic Cluster Supergiant TiO Band Strengths

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<th>SpT</th>
<th>(J-K) (_o)</th>
<th>(T_e) ((^\circ K))</th>
<th>(E_{62}^*) ((\AA))</th>
<th>(E_{71}^*) ((\AA))</th>
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### Table 4

Galactic Field Giant TiO Band Strengths

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<th>BS No.</th>
<th>SpT</th>
<th>(\langle J-K \rangle_o)</th>
<th>(T_e) ((^\circ K))</th>
<th>(E_{62}^*) ((\AA))</th>
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FIG. 3 - Observed equivalent width (in Å) of the TiO $\gamma(\Delta v=0)$ bands versus (J-K)$_0$ colour. Filled symbols represent galactic giants (circles) and supergiants (triangles). The adopted mean galactic giant (solid line) and supergiant (dashed line) relations are marked. Open symbols represent Large Magellanic Cloud supergiants from NGC 2100 (triangles), NGC 2004 (squares), NGC 1850 (crossed circle) and 30 Doradus ("Y") and Small Magellanic Cloud supergiants from NGC 330 (circles).
FIG. 4 - Observed equivalent width (in Å) of the TiO $\gamma'(\Delta v=0)$ bands versus (J-K)$_0$ colour. Symbols are the same as for Figure 3.
An empirical result that will be of importance in §IV(a) is the fact that for both the $\gamma$ and $\gamma'$ bands, at a given $(J-K)_0$ colour, the supergiant TiO equivalent widths are smaller than the giant TiO equivalent widths. This is also to be expected since it merely restates the well known fact that M supergiants have lower effective temperatures than M giants of the same spectral subclass (Lee 1970). (We note that the M giant and supergiant MK spectroscopic temperature classifications are based on the same criteria of the presence or absence of particular TiO bands. Thus giants and supergiants of the same spectral type should have the same TiO equivalent widths).

The scatter of LMC stars below the galactic sequences in Figure 3 and 4 clearly demonstrate the general result that the LMC supergiants in our sample have weaker TiO bands than galactic supergiants of the same $(J-K)_0$ colour (i.e., effective temperature). Although TiO bands are not clearly apparent in the spectra of many of the NGC 330 supergiants, equivalent widths for the absorption features in these spectra have been measured and are also smaller than for galactic supergiants of the same $(J-K)_0$ colour. The absorption measured in these spectra is expected to be predominantly due to atomic lines. Thus the above result also applies to the SMC stars. The consequences of this result were discussed in §III(a).

The large range in TiO band strengths seen among the LMC supergiants at a given $(J-K)_0$ colour warrants comment. Much of this scatter is due to the 30 Doradus supergiants which appear to form separate sequences at redder $(J-K)_0$ than the other LMC supergiants. These stars were shown to be cooler than the blue globular cluster supergiants in MH2, however, the
cause of their much weaker TiO bands, at constant (J-K)_o colour, is not understood. Evidence for photometric variability in two 30 Doradus supergiants was discussed in MHl. If further variable stars are present in the 30 Doradus sample, the scatter of these stars about the shifted sequences they appear to form may be due to variability, since their photometry and spectroscopy were not obtained concurrently. However, it is difficult to see how variability could be responsible for the shift itself. Glass (1979) reported variations of up to -0.1 mag in (J-K)_o in known variable LMC supergiants. The scatter in the LMC blue globular cluster data is less than for the 30 Doradus stars. However, significant differences in the TiO band strengths for LMC blue globular cluster supergiants of the same (J-K)_o colour remain. It is also not clear whether these differences are due to variability or to real band strength differences. Considerably less scatter was found previously in the 2.3 µm CO band strengths of the same stars. However, this may have been because the CO data were obtained concurrently with the broad band infrared observations.

A theoretical analysis is used in the following sections to interpret the smaller Magellanic Cloud TiO equivalent widths in Figures 3 and 4 in terms of TiO abundance deficiencies in the Magellanic Cloud stars.

IV. THEORETICAL BAND STRENGTHS

Synthetic spectra with a wavelength step size of 0.10 Å in the wavelength region from 7000 Å to 7600 Å (containing the Υ bands) and from 6000 Å to 6600 Å (containing the Υ' bands) have been computed using the spectrum synthesis code described in McGregor (1981). Synthetic spectra have been computed for supergiant model atmospheres from two model
atmosphere grids. The first is the expanded grid of Bell et al. (1976; hereafter BEGN) used in McGregor (1981). The uncertainties involved in extrapolating these models to lower temperatures (i.e., 3600K) were discussed in that paper. The TiO opacity was not included in the computation of the BEGN models and, as will be seen below, this omission has an important effect on the predicted TiO equivalent widths. The second grid is that of Johnson, Bernat and Krupp (1980; hereafter JBK) supplemented with similar unpublished metal deficient models generously supplied by Dr. H.R. Johnson. The original 60 depth point JBK models were used. These models retain the classical model atmosphere assumptions but represent a significant improvement in the accuracy of late-type supergiant model atmospheres since they include the line opacities of many molecular species, including TiO, in the opacity sampling formulation.

The line lists for both regions contain TiO, CN and atomic lines. The atomic lines are important in determining theoretical equivalent widths when the TiO absorption is small. Data for lines of the CN red system were taken from the same magnetic tape file described in McGregor (1981) and kindly provided by Dr. F. Querci, atomic line data were taken from Kurucz and Peytremann (1975) and the TiO line data were computed from published molecular data as described below. Lines from each of the three TiO triplet electronic systems (\( \alpha \), \( \gamma' \), and \( \gamma \)) were considered in constructing the TiO line lists. Following Collins (1975), only bands with vibrational quantum numbers up to 10 and Franck-Condon factors greater than 0.001 were considered. The rotational quantum numbers for each band were allowed to range up to \( J = 199 \) in the P, Q and R main branches. Electronic satellite branches were only considered for the \( \gamma' \) system (and then only for \( \Delta \Sigma = \pm 1 \), \( \Sigma \) being the component of the
electron spin along the internuclear axis) where they form ~30% of the rotational line intensity factor sum (Collins 1975). In the α and γ systems, satellite branches contribute <6% to this sum. Line positions were computed from formulae given by Phillips (1973) using molecular constants tabulated in that paper. The accuracy of the computed line positions was generally ± 0.2 Å. A-doubling in the $B^3Π$ state was ignored and no isotopic effects were included. $gf$-values for individual TiO lines (consisting of both $A$-components) were computed from the relation

$$gf = (2 - \delta_{0, \Lambda}) f_e (\lambda_{00}) \frac{\lambda_{00}}{\lambda_{\nu'\nu''}} q_{\nu'\nu''} S_J$$

where $\delta_{0, \Lambda}$ is the Kronecker delta symbol and is equal to zero for the TiO electronic states considered, $f_e (\lambda_{00})$ is the electronic oscillator strength, $\lambda_{\nu'\nu''}$ is the wavelength of the band origin, $q_{\nu'\nu''}$ is the Franck-Condon factor and $S_J$ is the normalized Hönl-London factor [i.e., $\sum_J S_J = (2J+1)(2S+1)$]. The Franck-Condon factors were taken from Collins (1975) and the Hönl-London factors computed from formulae in Kovacs (1969) using the normalization factors given in Whiting et al. (1973). The electronic oscillator strengths were those recommended by Krupp, Collins and Johnson (1978). The adopted TiO dissociation energy was 6.83 eV. This value was adopted by Krupp et al. after consideration of several recent determinations and is consistent with their recommended electronic oscillator strengths and is also the value used in the JBK model computations. All lines with equivalent widths ≥ 5 mÅ in the spectrum of the BEGN model with $T_e = 3600K$, log g = 0.0 and solar abundance were included in the final line lists. The line lists contain ~35,000 lines in the $\gamma$ region and ~58,000 lines in the $\gamma'$ region.
Previous theoretical studies of TiO absorption band strengths (Mould 1975, Bell and Gustafsson 1978) have required the TiO electronic oscillator strengths to be considerably smaller than the laboratory values recommended by Krupp et al. Following a similar procedure to previous workers, we first normalize the spectra based on BEGN models by computing synthetic spectra for the $T_e$/log $g$/[A/H]/$v_{\text{TURB}} = 4000/1.5/0.0/2$ BEGN model and adjust the recommended electronic oscillator strengths by a constant factor to force agreement with the TiO spectrum of α Tau (Johnson 1978). (Here we have adopted the usual notation where $T_e$ is the effective temperature, $g$ is the surface gravity, [A/H] is the heavy element abundance in the form $[\text{A/H}] = \log (\text{A/H})_{\odot} - \log (\text{A/H})_\odot$, and $v_{\text{TURB}}$ is the microturbulent velocity in km sec$^{-1}$). A reduction in the recommended electronic oscillator strengths by a factor of 20 is required for agreement with the spectrum of α Tau to be obtained. All synthetic spectra based on BEGN models discussed in this paper were computed with TiO electronic oscillator strengths reduced by this factor.

Theoretical equivalent widths for the synthesized TiO features have been computed by convolving the synthetic spectra with a Gaussian of $5\lambda$ full half width to approximate the observational resolution and measuring the equivalent widths, $E_{71}^*$ and $E_{62}^*$, in exactly the same way as for the observed spectra. The results for solar abundance BEGN models with $T_e = 4000, 3800$ and $3600$K, log $g = 0.0, 1.0$ and $2.0$, and $v_{\text{TURB}} = 2$ km sec$^{-1}$ are compared in Figures 5 and 6 with the mean galactic giant and supergiant lines from Figures 3 and 4. As in McGregor (1981), the $(J-K)_0$ colour for each model is taken to be the colour appropriate to the model
FIG. 5 - Theoretical equivalent width of the TiO $\gamma(\Delta v=0)$ bands versus (J-K)$_o$ colour diagram based on solar abundance models of the Bell et al. (1976) grid for electronic oscillator strengths reduced by a factor of 20 relative to recommended laboratory value. Models with $T_e = 4000$, 3800, and 3600K, log $g = 0.0$ (squares), 1.0 (triangles), and 2.0 (circles) are plotted. Models of equal surface gravity are joined by lines. The adopted mean galactic giant (solid line) and supergiant (dashed line) relations from Figure 3 are also shown.
Bell et al. Models

\[ E^* \]

\[ J - K \]

\[ 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \]
FIG. 6 - Theoretical equivalent width of the TiO Y′(Δν=0) bands versus (J-K)₀ colour diagram based on solar abundance models of the Bell et al. (1976) grid for electronic oscillator strengths reduced by a factor of 20 relative to recommended laboratory value. Symbols are the same as for Figure 5.
Bell et al. Models

In contrast with the analysis for the NO0 model, we find it possible to (1) match the 2608 Å series of a Y1 (Johannsen 74) with the 4000/1.5/0.5 model with reasonable accuracy, and (2) obtain reasonable agreement with the J-K and ultraviolet observations in the 8750 Å (J-K) plane. The NO0 and Ti0 models with the Ti0 electron and ultraviolet strengths as calculated by Knapp et al. are the outermost depth point in the 8750 Å (J-K) plane. The outermost depth point is strongly affected by the boundary conditions only adopted in the Ti0. The equivalent width data, as well as on the J-J models, are presented in the notes. The equivalent width data, as well as the electronic model parameter, are strongly affected by the boundary conditions.
effective temperature in the $T_e$ vs $(J-K)_0$ calibration described in MH2 (i.e., for $T_e = 4000, 3800, 3600, 3400K$ we set $(J-K)_0 = 0.87, 1.00, 1.11, \text{ and } 1.18 \text{ mag, respectively}).$

Even after a reduction of a factor of 20 in the electronic oscillator strengths, the theoretical equivalent widths based on the BEGN models do not show good agreement with the observations. This is especially true of the $Y'$ bands where equivalent widths far in excess of the observed values are predicted. Furthermore, a strong gravity dependence of the equivalent width for both bands is predicted in the opposite sense to the observed dependence noted in §III(b).

(b) Synthetic Spectra Based on the Johnson et al. Model Atmospheres

In contrast with the situation discussed above for the BEGN models, we find it possible to, (1) match the TiO spectrum of a Tau (Johnson 1978) with the JBK 4000/1.5/0.0/2 model to reasonable accuracy, and (2) obtain reasonable agreement with the galactic giant and supergiant observations in the $E^*$ vs $(J-K)_0$ planes using the JBK models with the TiO electronic oscillator strengths recommended by Krupp et al., if the outer-most depth point of the 60 depth point JBK models is omitted. The outer-most depth point in many of the JBK models is strongly affected by the boundary conditions they adopt in that it has an unreasonably low temperature which affects the computed TiO spectrum. The equivalent width data based on the JBK models are plotted in Figures 7 and 8 for $T_e = 4000, 3800, 3600$ and $3400K, \log g = 0.0, 1.0, \text{ and } 2.0$. Lines for metallicities of $[A/H] = 0.0, -0.5, -1.0, \text{ and } -1.5$ are shown for the $Y$ bands (Fig. 7). To economise on computing time, only solar abundance lines have been computed for the $Y'$ bands (Fig. 8). These data are also tabulated in an
FIG. 7 - Theoretical equivalent width of the TiO $\gamma$($\Delta v=0$) bands versus (J-K)$_0$ colour diagram based on models of the Johnson et al. grid for electronic oscillator strengths equal to the recommended laboratory values. Models with $T_e = 4000$, 3800, 3600, and 3400K, log $g = 0.0$ (squares), 1.0 (triangles), and 2.0 (circles) are plotted for [A/H] = 0.0 (filled), -0.5 (half filled) and -1.0 (open). Models with log $g = 1.0$ and [A/H] = -1.5 (crosses) are also plotted. The adopted mean galactic giant (solid line) and supergiant (dashed line) relations from Figure 3 are also shown.
Johnson et al. Models

\[ E^* \]

\[ J - K \]

Graph showing Johnson et al. Models with various curves and symbols.
FIG. 8 - Theoretical equivalent width of the TiO $\gamma'(\Delta v=0)$ bands versus (J-K)$_0$ colour diagram based on models of the Johnson et al. grid for electronic oscillator strengths equal to the recommended laboratory values. Only models with solar abundance are shown. Symbols are as for Figure 7.
Johnson et al. Models

The diagram shows the relationship between predicted atmospheric properties and observed data. The models are labeled I, II, and III, with III showing the best agreement with the observations. The absolute values of the predicted quantities are at least slightly higher than observed, however, the agreement with the model predictions is encouraging, and re-fitting the models using a new set of variables will improve the agreement. The diagram also indicates the importance of accounting for the effects of magnetic fields and internal gravity waves in the models.
Appendix. The predicted solar abundance relations have the same slope and width as the galactic giant/supergiant relations (if we equate the log g = 2.0 models with the giant line and the log g = 0.0 models with the supergiant line), and the sense of the dependence of equivalent width on surface gravity is generally in agreement with the observations. The absolute values of the predicted equivalent widths are still slightly larger than observed, however, the agreement that is obtained using laboratory oscillator strengths is encouraging and we feel justified in applying these models to the analysis of the TiO band strengths in the metal deficient Magellanic Cloud supergiants. Reducing the microturbulent velocity to the value of 1 km sec\(^{-1}\) used by JBK in the computation of their models improves the agreement for galactic giants. However, it is unlikely that such a low microturbulent velocity applies to the supergiants as well.

(c) Why do the Predictions Differ?

The cause of the dramatic differences between predictions based on the two model atmosphere grids can be traced to the different temperature structures in the outer layers of models from each grid. The true temperature structure in the outer layers of late-type stars is determined by a balance, between CO and CN surface cooling and TiO surface heating (see, e.g., Carbon 1979). The JBK model computations include both these effects. The BEGN model computations did not include the effects of TiO opacity and are consequently significantly cooler in their outer layers than JBK models with the same parameters. At these cooler temperatures the TiO number density increases markedly and would, if the TiO opacity was included, lead to a significant surface heating effect which would
return the TiO number density to a lower equilibrium value. In this way, the TiO opacity can have an effect on the temperature structure even in stars that are too hot to show prominent TiO bands. The significant effect in this sense that the TiO opacity has on the atmospheric structure of the metal deficient K2 giant α Boo has been recognised by Johnson et al. (1977).

The differences discussed above can be clearly seen from a detailed comparison of the 4000/1.0/0.0 models based on each grid (Figs. 9 and 10). For \( T_{\text{ROSS}} < -2.5 \) temperature differences exist between the models in the sense that the BEGN model is cooler than the JBK model by up to -250K. This temperature difference leads to an increase of -1.7 dex in the TiO number density at the surface of the BEGN model compared with the JBK model. The absorption characteristics of the atmosphere at TiO line wavelengths are drastically modified by this increased TiO number density. The CO and CN number density distributions and the electron density distribution are only slightly affected by the different temperature structures.

Since the BEGN models were used in McGregor (1981) to analyse the 2.3 μm CO band strengths in the Magellanic Cloud supergiants, it is important to compare the CO band strength predictions of the BEGN and JBK models. This comparison, for selected models (Table 5), shows that although the quantitative heavy element abundance and microturbulence results may be slightly altered, the conclusions reached in McGregor (1981) that carbon may be depleted in the NGC 330 supergiants will not be affected because the reduction in CO band strength introduced by using the JBK rather than BEGN models is largest for solar abundance models, where the TiO heating effect is strongest. Thus the difference between
FIG. 9 - Detailed depth dependence of atmospheric structure for 4000/1.0/0.0 model from Johnson et al. grid. The depth parameter (abscissa) is the logarithm of the Rosseland mean opacity depth. Plotted are temperature (solid), pressure (dashed), logarithmic electron density (dot-dashed), logarithmic TiO number density (dotted), logarithmic CO number density (double dot-dashed), and logarithmic CN number density (dash-dashed).
FIG. 10 - Detailed depth dependence of atmospheric structure for 4000/1.0/0.0 model from Bell et al. (1976) grid. Parameters plotted are as for Figure 9. Temperatures in the outer layers of the Bell et al. models are lower than in the Johnson et al. models causing a large increase in the TiO number density in the outer layers.
solar abundance and metal deficient models is reduced slightly by using the JBK models, not increased as would be required to simply explain the NGC 330 supergiant CO data.

Table 5

Comparison of CO Indices Based on JBK and BEGN Models

<table>
<thead>
<tr>
<th>( T_e / \log g / [A/H] )</th>
<th>CO\textsubscript{BEGN}</th>
<th>CO\textsubscript{JBK}</th>
<th>( \Delta \text{CO} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000/1.0/0.0</td>
<td>.22</td>
<td>.21</td>
<td>-.01</td>
</tr>
<tr>
<td>3600/1.0/0.0</td>
<td>.27</td>
<td>.22</td>
<td>-.05</td>
</tr>
<tr>
<td>4000/1.0/-1.0</td>
<td>.15</td>
<td>.15</td>
<td>.00</td>
</tr>
<tr>
<td>3600/1.0/-1.0</td>
<td>.19</td>
<td>.18</td>
<td>-.01</td>
</tr>
</tbody>
</table>

We also note that the sensitivity of the TiO band strength to the temperature structure must place severe constraints on the importance of sphericity effects in supergiant atmospheres because the inclusion of sphericity effects in model computations leads to even lower temperatures in the outer layers (Schmid-Burgk, Scholz and Wehrse 1981). The TiO band strengths predicted from such models are expected to be grossly inconsistent with the observed supergiant TiO band strengths. In fact, to obtain better agreement between theoretical and observed TiO equivalent widths (Figs. 7 and 8), it may be necessary for the temperatures in the outer atmospheric layers of the supergiant models to be slightly hotter than those predicted by the JBK models. The heating effect associated with the presence of a chromosphere may contribute to this additional heating in the outer layers of real stars (cf., Ayers and Linsky 1975).
V. TIO ABUNDANCES IN MAGELLANIC CLOUD SUPERGIANTS

(a) Heavy Element Abundances

The Magellanic Cloud blue globular cluster data for the 7100Å bands are replotted in Figure 11 along with the mean galactic supergiant line. As noted above, the cooler 30 Doradus supergiants appear to have even weaker TiO bands than the blue globular cluster supergiants. We do not compare these stars with our theoretical predictions in Figure 11 because the accuracy of our line list and of our estimates of the model J-K colours are uncertain at these lower temperatures and if the 30 Doradus supergiants are variable stars, the static model atmospheres used here may not be adequate representations of these stars.

In analysing the Magellanic Cloud blue globular cluster data, we use only the JBK models with log g = 1.0 because the gravity effect is small and most of the metal deficient models in our possession were computed with this surface gravity. Because the theoretical solar abundance TiO equivalent widths do not precisely agree with the observations of galactic giants and supergiants (Fig. 7), we adopt the procedure of scaling all the predicted TiO equivalent widths by 0.6 to enable a differential analysis of the band strengths of galactic and Magellanic Cloud supergiants to be undertaken. The scaled, predicted lines for [A/H] = 0.0, -0.5, -1.0, and -1.5 are plotted in Figure 11.

Comparison of the observed data with the theoretical predictions in Figure 11 shows that, on average, the LMC TiO band strengths are consistent with a metallicity of [A/H] ~ -0.5 for these stars. The mean abundance derived from the LMC supergiant TiO bands is, therefore, consistent with the abundances indicated previously from the CO and CN bands in these stars (MH2, McGregor 1981). Thus, on average, the CNO
FIG. 11 - Comparison of observed equivalent widths of the TiO $\gamma(\Delta v=0)$ bands and predictions based on the Johnson et al. models. The predicted equivalent widths have been scaled by 0.6 to match the solar abundance line to the adopted mean galactic supergiant relation (heavy dashed line) from Figure 3. Plotted symbols are the same as for Figure 3. The light dashed line shows the theoretical equivalent widths for $[A/H] = -0.5$ with the TiO line opacity neglected.
The [A/H] values for the SMC supergiants are also consistent with the [A/H] = -0.3 values obtained for the theoretical models. However, we do not have sufficient data to determine the values of [A/H] for the SMC supergiants. The effects of [A/H] on the theoretical models are also included in the calculations. The theoretical models are expected to be consistent with the observed values for [A/H] = -0.3 from their positions in Figure 17. The [A/H] values for the SMC supergiants are consistent with the mean abundance expected for Population I objects.
abundances in the LMC supergiants appear to be consistent with the heavy element abundances in these stars, as indicated from the titanium component of the TiO molecule. The scatter of the individual LMC points in Figure 11 may be due to some extent to individual variations in the CNO/A abundance ratios (see below).

The NGC 330 (SMC) supergiant TiO equivalent widths are also consistent with the predicted \([A/H] = -0.5\) line in Figure 11. As mentioned above, the TiO bands in these stars are weak, so a significant fraction of the absorption measured by the equivalent widths is due to atomic lines. An estimate of this fraction can be obtained from a comparison with the dashed line in Figure 11 which shows the predicted equivalent widths for \([A/H] = -0.5\) models with the TiO line opacity neglected. The effects of atomic lines have been included in the theoretical calculations and are therefore allowed for in the theoretical lines for different metallicities in Figure 11. However, we do not claim to have synthesized the equivalent widths of atomic features to high accuracy, so the positions of these theoretical lines are expected to be less certain at small equivalent widths. After due consideration of this uncertainty and of the effect on the TiO band strength of the possible carbon depletion indicated in McGregor (1981) for these stars (see below), we place an upper limit on the metallicity of the NGC 330 supergiants of \([A/H] \leq -0.5\) from their positions in Figure 11. This limit is consistent with the mean abundance expected for Population I objects in the SMC (van den Bergh 1975) and with both the alternative chemical compositions suggested previously for these particular stars from an analysis of their 2.3 \(\mu\)m CO indices (McGregor 1981). Consequently, this limit does not allow us to distinguish between these alternatives.
(b) **Sensitivity to Other Parameters**

Implicit in the above comparisons with the predicted metal deficient lines in Figure 11 are the assumptions that, (1) the CNO/A ratios in the Magellanic Cloud stars do not differ from their solar values, and (2) the mean microturbulent velocities of the Magellanic Cloud and galactic supergiants are the same. The differential effects of decreasing the O/A and C/A ratios are shown in Tables 6 and 7, respectively. A slight decrease in the oxygen abundance (as might be expected if the atmosphere is heavily mixed) is predicted to reduce the TiO equivalent widths because the TiO number density depends directly on the oxygen abundance. The sensitivity to this effect (Table 6) is likely to have been overestimated here because we have neglected the effect on the model structure of the lower oxygen abundance which should act to increase the TiO band strength. Variations in the O/A ratios in the LMC supergiants could contribute to their observed scatter. Decreasing the carbon abundance (the dominant effect of mixing) is predicted to cause the TiO equivalent width to *increase* because oxygen liberated as the CO number density decreases is partially used in the formation of more TiO molecules. The sensitivity to this effect (Table 7) is also likely to be overestimated due to the neglected effect on the model structure. Since carbon may be depleted in the NGC 330 supergiants relative to heavier elements, this effect may be responsible for the NGC 330 supergiants having slightly larger measured TiO equivalent widths than a typical Population I SMC metallicity of [A/H] = -0.8 combined with the predicted lines in Figure 11 would suggest. Carbon abundance variations in the LMC supergiants, if present, could contribute to their observed scatter. However, this possibility can be excluded because such variations are not consistent with the tighter LMC relation found in the (CO) vs (J-K) plane for these stars (McGregor 1981).
Table 6

Differential Effect of Oxygen Depletion

<table>
<thead>
<tr>
<th></th>
<th>$E_{71}^*([O/A]=0.0)$</th>
<th>$E_{71}^*([O/A]=-0.1)$</th>
<th>$\Delta$</th>
<th>$0.6\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000/1.0/-0.5</td>
<td>35</td>
<td>27</td>
<td>-8</td>
<td>-4.8</td>
</tr>
<tr>
<td>3600/1.0/-0.5</td>
<td>132</td>
<td>106</td>
<td>-26</td>
<td>-15.6</td>
</tr>
<tr>
<td>4000/1.0/-1.0</td>
<td>18</td>
<td>15</td>
<td>-3</td>
<td>-1.8</td>
</tr>
<tr>
<td>3600/1.0/-1.0</td>
<td>97</td>
<td>69</td>
<td>-28</td>
<td>-16.8</td>
</tr>
</tbody>
</table>

Table 7

Differential Effect of Carbon Depletion

<table>
<thead>
<tr>
<th></th>
<th>$E_{71}^*([C/A]=0.0)$</th>
<th>$E_{71}^*([C/A]=-0.5)$</th>
<th>$\Delta$</th>
<th>$0.6\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000/1.0/-0.5</td>
<td>35</td>
<td>48</td>
<td>13</td>
<td>7.8</td>
</tr>
<tr>
<td>3600/1.0/-0.5</td>
<td>132</td>
<td>156</td>
<td>24</td>
<td>14.4</td>
</tr>
<tr>
<td>4000/1.0/-1.0</td>
<td>18</td>
<td>26</td>
<td>8</td>
<td>4.8</td>
</tr>
<tr>
<td>3600/1.0/-1.0</td>
<td>97</td>
<td>124</td>
<td>27</td>
<td>16.2</td>
</tr>
</tbody>
</table>
The sensitivity of the predicted TiO equivalent widths to the microturbulent velocity is indicated in Table 8. This sensitivity is probably underestimated due to the neglected effect on the model structure. However, variations in the microturbulent velocities of the LMC supergiants are unlikely to cause the observed scatter because the 2.3 µm CO bands are more sensitive to microturbulence and, as noted above, these same LMC stars show less scatter in the (CO)_o vs (J-K)_o plane.

Table 8

Differential Effect of Changing the Microturbulent Velocity

<table>
<thead>
<tr>
<th>E^*<em>{71}(v</em>{TURB}=2)</th>
<th>E^*<em>{71}(v</em>{TURB}=1)</th>
<th>Δ</th>
<th>0.6Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000/1.0/0.0</td>
<td>62</td>
<td>55</td>
<td>-7</td>
</tr>
<tr>
<td>3600/1.0/0.0</td>
<td>155</td>
<td>134</td>
<td>-21</td>
</tr>
<tr>
<td>4000/1.0/-1.0</td>
<td>18</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>3600/1.0/-1.0</td>
<td>97</td>
<td>82</td>
<td>-15</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

Observations of the TiO band strengths in our Magellanic Cloud and galactic supergiants have shown that the TiO bands in Magellanic Cloud supergiants are weaker than in galactic supergiants of the same (J-K)_o colour (i.e., effective temperature) and that the TiO spectra of Magellanic Cloud supergiants are generally well matched by the TiO spectra of hotter galactic supergiants. These results also apply to the LMC and SMC supergiant samples of Humphreys (1979a, b) and suggest that the shift of the
mean spectral types of late-type supergiants in the Galaxy, LMC, and SMC
to earlier spectral types, in that order, is due to direct abundance,
rather than evolutionary temperature, effects. The 30 Doradus supergiants
appear to form separate sequences in the $E^*$ vs $(J-K)_0$ planes at redder
colours and weaker TiO band strengths than the LMC blue globular cluster
supergiants. The reason for this separation is not understood.

The model atmospheres of Johnson et al., which include the effects
of the TiO opacity, have given encouraging agreement between the predicted
and observed TiO band strengths for galactic stars. Consequently, we
believe that the differential effects of abundance deficiencies on the
TiO band strengths have also been predicted with reasonable accuracy
using similar metal deficient models supplied by Dr. H.R. Johnson.

On average, the LMC blue globular cluster supergiant TiO equivalent
widths are consistent with a metallicity of $[A/H] = -0.5$ as was found
previously from the strengths of their CN bands (MH2) and CO bands
(McGregor 1981). Thus, on average, the heavy element abundance in the
LMC supergiants, as indicated from the titanium component of the TiO
molecule, appears to be consistent with the CNO abundances in these stars.
Considerable scatter exists in the TiO band strengths of individual LMC
supergiants at constant $(J-K)_0$, and it is not clear whether this scatter
is due to real band strength differences or to stellar variability.
Oxygen abundance differences between individual stars may contribute to
the observed scatter of LMC stars, however, carbon abundance differences
and microturbulence differences in the LMC stars can be excluded on the
basis of their measured 2.3 $\mu$m CO indices.
The weakness of the TiO bands in the SMC stars leads to an upper limit of \([A/H] \leq -0.5\) being placed on the metallicity of the NGC 330 (SMC) supergiants. This limit is consistent with both the abundance alternatives suggest for these stars from their 2.3 \(\mu m\) CO indices (McGregor 1981) and so does not allow us to distinguish between these alternatives.

Oxygen abundance deficiencies in late-type stars are predicted to cause the TiO band strength to decrease, while carbon abundance deficiencies are predicted to cause the TiO band strength to increase.

ACKNOWLEDGEMENTS

The author is indebted to Drs. H.R. Johnson and B. Gustafsson for permitting the use of unpublished model atmospheres and to Dr. F. Querci for allowing access to his ATLAS molecular line list tape. The author also wishes to thank Dr. P.R. Wood for allowing the twilight of a 74" telescope run to be used for this project, Drs. D.A. Allen and A.R. Hyland for permitting the use of their 30 Doradus supergiant spectra, Dr. M.S. Bessell for suggesting the red TiO bands as a source of abundance information, Dr. J.E. Norris for informative discussions, and Dr. D.L. Lambert for supplying empirical TiO line position data. It is a pleasure to also thank Dr. A.R. Hyland for his continued interest in this project and for commenting on the manuscript. The author acknowledges the support of an Australian Commonwealth Postgraduate Research Award which permits unlimited access to the UNIVAC 1100/82 computer operated by the Computer Services Centre of the Australian National University, without which this research would not have been possible.
### Table A1

**Predicted TiO $\gamma(\Delta v=0)$ Band Equivalent Widths ($E_{71}^*$)**

Based on Johnson *et al.* Models. ($v_{TURB} = 2$ km sec$^{-1}$)

(a) $[A/H] = 0.0$

<table>
<thead>
<tr>
<th>$T_e$</th>
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<th>2.0</th>
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<tr>
<td>3400</td>
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(b) $[A/H] = -0.5$

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<td>4000</td>
<td></td>
<td>-</td>
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<tr>
<td>3400</td>
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(c) $[A/H] = -1.0$

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<td>-</td>
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<td>3400</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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</table>
(d) $[\text{A/H}] = -1.5$

<table>
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<th>$T_e$</th>
<th>$\log g$</th>
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<tr>
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</tr>
<tr>
<td>3600</td>
<td>-</td>
</tr>
<tr>
<td>3400</td>
<td>-</td>
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</tbody>
</table>

Table A2
Predicted TiO $\gamma'(\Delta v=0)$ Band Equivalent Widths ($E_{62}$)
Based on Johnson et al. Models. ($[\text{A/H}] = 0.0, v_{\text{TURB}} = 2 \text{ km sec}^{-1}$)

<table>
<thead>
<tr>
<th>$T_e$</th>
<th>$\log g$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
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<td>3600</td>
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<tr>
<td>3400</td>
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REFERENCES


CHAPTER 6

ANALYSIS OF MAGELLANIC CLOUD LATE-TYPE SUPERGIAN T SPECTRA IN THE BLUE SPECTRAL REGION

P.J. McGregor

ABSTRACT

Intermediate resolution blue spectra for five Magellanic Cloud and two galactic late-type supergiants have been analysed using a spectrum synthesis approach. Based on their G band spectra, it is shown that carbon is deficient relative to heavier elements by the same factor in all the supergiants studied to within $\pm 0.2$ dex. The mean absolute value of this deficiency is determined to be $0.6 \pm 0.2$ dex. This result leads to a reappraisal of the chemical abundances suggested from the 2.3 $\mu$m CO indices for supergiants in the SMC blue globular cluster NGC 330. These stars now appear to have a mean heavy element abundance in the range $-0.5 \leq [A/H] \leq -1.0$, a mean carbon deficiency of $[C/A] = -0.6 \pm 0.2$ and, in order to fit their observed 2.3 $\mu$m CO indices using a low value of $[A/H] = -1.0$, they are required to have a mean microturbulent velocity of $2.5 \pm 0.5$ km sec$^{-1}$. The LMC supergiants are found to have a mean heavy element abundance of $[A/H] = -0.5 \pm 0.2$, a mean carbon deficiency of $[C/A] = -0.6 \pm 0.2$ and a mean microturbulent velocity of $4.5 \pm 0.5$ km sec$^{-1}$. 
I. INTRODUCTION

In an earlier paper in this series (McGregor 1981a), an analysis of the 2.3 µm CO indices for a sample of Magellanic Cloud late-type supergiants in blue globular clusters revealed that the chemical abundance of supergiants in the Small Magellanic Cloud (SMC) cluster NGC 330 were probably unlike those expected for Population I objects in that galaxy. Either heavy element abundances as low as [A/H] = -1.5 and normal carbon abundances (i.e., [C/A] = 0.0) or [A/H] = -1.0 and [C/A] = -0.5 were suggested to explain the measured CO indices for these stars (here \( [a/b] = \log (a/b)_* - \log (a/b)_g \)). However, the possibility that the abundances in these stars were normal for the SMC (i.e., [A/H] = -1.0), but that their mean microturbulent velocity was significantly lower than for similar galactic and Large Magellanic Cloud (LMC) stars could not be excluded using only the low resolution CO index data. TiO bands are weak or absent in the NGC 330 supergiants and while they are consistent with low metallicity in these stars, they can not be used to distinguish between these abundance alternatives. Mean abundances consistent with those expected for Population I objects in the LMC were suggested from the measured CO indices for the LMC supergiants. A similar result for the LMC supergiants was also suggested from an analysis of low resolution TiO band strength data for these stars (McGregor 1981b).

Intermediate resolution blue spectra of a small number of these SMC and LMC supergiants are used in this paper to obtain further estimates of their carbon abundances from analyses of G band (CH) spectra and of their heavy element abundances and microturbulent velocities from analyses of atomic line spectra.

1 McGregor (1981a) = Chapter 4
2 McGregor (1981b) = Chapter 5
II. OBSERVATIONS

Intermediate resolution spectra were obtained in 1978 September and November and 1979 January using the R.G.O. spectrograph/IP.C.S. combination on the 3.9m Anglo-Australian Telescope for many of the Magellanic Cloud and galactic cluster supergiants studied in McGregor and Hyland (1981, hereafter MH2) \(^3\) and for a number of suspected galactic field M supergiants from the objective prism survey of Albers (1972). Grating 2 was used in the "blaze to collimator" configuration with the 25 cm focal length camera giving a nominal dispersion of 16\(\AA\)/mm over the wavelength region \(-4160 - 4630\\AA\). A slit width of 200 \(\mu\)m was used, giving a resolution of \(-0.7\\AA\) at the detector. The sky-subtracted spectra were smoothed with a Gaussian filter of full half width equal to \(-0.4\\AA\) and are plotted in an Appendix as counts/channel vs wavelength. One resolution element corresponds to approximately three channels in these spectra.

III. ANALYSIS

(a) Qualitative Comparison of Magellanic Cloud and Galactic Spectra

The most obvious difference between the spectra presented in the Appendix is their appearance in the region shortward of the G band (i.e., \(\lambda \leq 4310\\AA\)). The three NGC 330 spectra show substantial flux in this region, whereas most of the galactic and LMC supergiants are heavily blanketed. The spectrum of one galactic field star, CD \(-43^\circ\) 4361 has the same appearance as the NGC 330 supergiants in this region. No spectral type is available for this star. However, if we assume that this star lies on the mean galactic supergiant line in the \((CO)_o\) vs \((J-K)_o\) plane

\(^3\) MH2 ≡ Chapter 3
(MH2), its observed J-K colour and CO index can be used to estimate the reddening to the star. This procedure leads to a dereddened J-K colour of 0.66 mag for CD -43° 4361 which corresponds to an effective temperature of -4650K (MH2) - much hotter than we expect for a galactic M supergiant. Since we know that the NGC 330 supergiants are hotter than the LMC and galactic supergiants (MH2), it is likely that this spectroscopic difference is due to a temperature difference, rather than to an abundance difference, between the supergiants in each galaxy.

Apart from this difference, the spectra of the Magellanic Cloud and galactic supergiants are remarkably similar; we can find no qualitative evidence for abundance differences between these stars from the appearance of their blue spectra. Since the continuous opacity in late-type supergiants is dominated by the H ion opacity which depends on the metal abundance through the electron pressure and since the atomic line opacity in the blue is dominated by neutral lines which also depend on the first power of the metal abundance, it is to be expected that the strengths of the atomic lines will, to a first approximation, be independent of metallicity in late-type supergiant stars. This fact, combined with our result noted above, explains why Humphreys (1979) detected no strong spectroscopic peculiarities in the Magellanic Cloud spectra she classified, even though their TiO band strengths were significantly weaker than in galactic supergiants of the same effective temperature (McGregor 1981b). Nevertheless, the following theoretical investigation shows that some features do show discernable sensitivities to the atmospheric parameters.
(b) **Spectrum Synthesis Analysis**

(i) **Technique**

The spectrum synthetic code described in McGregor (1981a) has been used with the model atmosphere grid of Bell *et al.* (1976), supplemented with six log g = 0.0 models kindly provided by Dr. B. Gustafsson, to produce synthetic spectra in the region of the G band (4295 - 4330Å) and in the region 4500 - 4600Å with a wavelength step size of 0.05Å. The line list for the G band region is exactly that used by Cottrell and Norris (1978) and contains CH lines with parameters computed by these authors and atomic lines from the compilation of Kurucz and Peytremann (1975). The oscillator strengths of many lines in this list have been adjusted by Cottrell and Norris to fit the solar spectrum. The line list for the 4500 - 4600Å region contains only atomic lines from Kurucz and Peytremann (1975). The gf-values of many of these lines were adjusted to obtain agreement with the spectrum of α Boo (Griffin 1968) using the model $T_e/\log g/[A/H] = 4250/1.7/-0.6$ (Lambert and Ries 1977) and a microturbulent velocity of 2 km sec$^{-1}$. (Here, $T_e$ is the effective temperature, $g$ is the surface gravity, and $[A/H]$ is the heavy element abundance). The atomic line broadening was assumed to be due to radiation broadening and van der Waal's broadening. Test calculations for models with $T_e/\log g/[A/H] = 3800/0.0/0.0$ from the Bell *et al.* (1976) and Johnson, Bernat and Krupp (1980) grids showed that the shortcomings of the Bell *et al.* model atmospheres at low temperatures discussed in McGregor (1981b) do not significantly affect the computed spectra in these wavelength regions. The computed spectra have been convolved with a Gaussian filter of 0.8Å full half width to match the resolution of the observed spectra and are plotted as relative numbers of photons versus wavelength for comparison with the observations.
In the following, we compare the observed and computed spectra in the 4500 - 4600 Å region to obtain estimates of the heavy element abundances and microturbulent velocities and then use these values as a basis for deriving carbon abundances from the G band spectra. Only those stars within the range of the extended Bell et al. (1976) model atmosphere grid will be subjected to detailed analysis. Atmospheric parameters for these stars (MH2) are listed in Table 1.

Table 1
Atmospheric Parameters of Selected Supergiants

<table>
<thead>
<tr>
<th></th>
<th>Te</th>
<th>log g</th>
<th>Model (Te/log g)</th>
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<td>NGC 330/B20</td>
<td>4550</td>
<td>.99</td>
<td>4550/.99</td>
</tr>
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<td>3950/.35</td>
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<td>4000</td>
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<td>3950/.35</td>
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<td>NGC 2100/C12</td>
<td>3800</td>
<td>.33</td>
<td>3800/.3</td>
</tr>
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<td>.08</td>
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<td>.12</td>
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<td>CD -60° 3621</td>
<td>3750</td>
<td>.50</td>
<td>3800/.3</td>
</tr>
</tbody>
</table>

(ii) NGC 330 Abundances

The atmospheric parameters of the three NGC 330 supergiants for which we have spectra make each of these stars suitable for detailed analysis. The spectrum of NGC 330/B40 is of lower quality and will only be compared with the synthesized spectra in the 4500 - 4600 Å region. The spectra for each of the NGC 330 supergiants are now discussed in turn.
NGC 330/B20: The sensitivity of synthetic spectra in the G band and 4500–4600Å regions to changes in effective temperature, surface gravity, heavy element abundance and microturbulence at the parameters appropriate to NGC 330/B20 are shown in Figure 1. The spectra are quite insensitive to changes in temperature of 200K and in gravity of 1.0 dex in both regions. A change in microturbulence from 2 to 4 km sec\(^{-1}\) causes a general increase in the level of absorption in both the G band and 4500–4600Å regions. The microturbulence-sensitive feature at λ4534 does not reproduce the observed spectra well and has been discounted in the following assessments. The 4500–4600Å region is most sensitive to heavy metallicity, showing a generally lower line blocking over the whole region for the change in abundance from [A/H] = -1.0 to -0.5. The feature at λ4541 is one of the few features in this region which show a substantial abundance sensitivity and only a small sensitivity to microturbulence. This feature will be used as the major indicator of heavy metallicity in the following comparisons. Except for the FeI line at λ4325, the G band region is quite insensitive to a heavy metallicity change of 0.5 dex. We note that at this temperature the feature at λ4324 which is due entirely to CH absorption is insensitive to changes in both the overall heavy element abundance and the microturbulent velocity. Consequently, carbon abundances of reasonable precision can be obtained without a precise knowledge of the heavy element abundance and microturbulent velocity.

Estimates of the microturbulent velocity and heavy element abundance have been made by determining the microturbulent velocities which give optimum fits to the observed spectra in the 4500–4600Å region for a range of heavy element abundances. These self-consistent abundance/microturbulence pairs for NGC 330/B20 are listed in Table 2 and the
FIG. 1 - Sensitivities of the computed spectra to changes in the atmospheric parameters for parameters appropriate to NGC 330/B20. The light line in each frame is the spectrum for $T_e$/log g/[A/H]/$v_TURB = 4500/1.0/-1.0/2$. From top to bottom, the heavy line in each frame is the spectrum for 4300/1.0/-1.0/2, 4500/0.0/-1.0/2, 4500/1.0/-0.5/2, 4500/1.0/-1.0/4. Spectral features discussed in the text are indicated.
FIG. 2 - Comparison of observed and computed spectra for NGC 330/B20. The heavy line in each frame is the spectrum of NGC 330/B20. Model spectra (light lines) are for $T_{e}/\log g = 4550/0.99$ and $[A/H]/v_{\text{TURB}}$ parameters as marked in the right-hand portion of each frame. G band spectra are computed for these parameters and the upper and lower carbon abundance limits listed in Table 3. Spectral features discussed in the text are indicated.
Table 2
Consistent Abundance/Microturbulence Pairs
for NGC 330/B20

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>$v_{\text{TURB}}$</th>
<th>Quality of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0 - 3.0</td>
<td>Fair: $\lambda 4541$ discrepant</td>
</tr>
<tr>
<td>-0.5</td>
<td>2.5 - 4.5</td>
<td>Good</td>
</tr>
<tr>
<td>-1.0</td>
<td>&gt;5.5</td>
<td>Fair</td>
</tr>
<tr>
<td>-1.5</td>
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<td>No agreement possible</td>
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Table 3
Carbon Abundance Estimates for NGC 330/B20

<table>
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<th>[C/A]</th>
<th>Comments</th>
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<td>0.0</td>
<td>2.0</td>
<td>-0.4 ± 0.2</td>
<td>FeI $\lambda 4325$ prediction too strong</td>
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<tr>
<td>-0.5</td>
<td>3.5</td>
<td>-0.4 ± 0.2</td>
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</tr>
<tr>
<td>-1.0</td>
<td>6.0</td>
<td>-0.4 ± 0.2</td>
<td>FeI $\lambda 4325$ agreement good</td>
</tr>
</tbody>
</table>
corresponding synthetic spectra are compared with NGC 330/B20 in Figure 2. The quality of the fits to the observed spectrum is clearly variable and allows limits to be estimated for the possible heavy element abundance. A metallicity of \([A/H] = -1.5\) can be excluded for NGC 330/B20 because the observed spectrum cannot be matched for any reasonable microturbulence. Solar heavy element abundance is also unlikely because of the lack of agreement with the abundance sensitive feature at \(\lambda 4541\). The best match with the spectrum of NGC 330/B20 is for a metallicity of \([A/H] = -0.5\).

The Ball feature at \(\lambda 4554\) is strong in all the observed supergiant spectra (see Appendix). No model atmospheres with \([A/H] = -1.5\) are available for the remaining stars.

Using the abundance/microturbulence pairs derived above, we now compare the G band region of NGC 330/B20 with synthetic spectra for different carbon abundances. We attempt to fit the \(\lambda 4324\) feature which is due entirely to CH absorption and the \(\lambda 4310-4313\) region which is predominantly due to CH absorption. The carbon abundances obtained for NGC 330/B20 are listed in Table 3 (relative to \(\log E_e = 8.67\), Lambert 1978) and the corresponding spectra for the upper and lower carbon abundance limits are displayed in Figure 2. The poor fit to the FeI \(\lambda 4325\) line for solar heavy element abundance supports the claim that this star has lower than solar metallicity.

**NGC 330/B10:** The sensitivity of spectra at the cooler temperature of NGC 330/B10 to temperature, gravity, abundance and microturbulence effects are shown in Figure 3. The spectra remain insensitive to temperature and gravity changes, but the sensitivities to abundance and microturbulence changes are somewhat larger. The \(\lambda 4541\) feature remains predominantly abundance sensitive and the \(\lambda 4324\) CH feature remains
FIG. 3 - Sensitivities of the computed spectra to changes in the atmospheric parameters for parameters appropriate to NGC 330/B10 and NGC 330/B40. The light line in each frame is the spectrum for $T_e$/log $g$/[A/H]/$v_{TURB} = 4000/0.5/-1.0/2$. From top to bottom, the heavy line in each frame is the spectrum for $3800/0.5/-1.0/2$, $4000/-0.5/-1.0/2$, $4000/0.5/-0.5/2$, $4000/0.5/-1.0/4$. Spectral features discussed in the text are indicated.
FIG. 4 - Comparison of observed and computed spectra for NGC 330/B10. The heavy line in each frame is the spectrum of NGC 330/B10. Model spectra (light lines) are for $T_e/\log g = 3950/0.35$ and $[\text{A/H}]_{\nu_{\text{TURB}}}$ parameters as marked in the right-hand portion of each frame. G band spectra are computed for these parameters and the upper and lower carbon abundance limits listed in Table 5. Spectral features discussed in the text are indicated.
Table 4
Consistent Abundance/Microturbulence Pairs
for NGC 330/B10

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>( v_{\text{TURB}} )</th>
<th>Quality of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0 - 2.5</td>
<td>Fair: ( \lambda 4541 ) and ( \lambda \lambda 4527, 4529, 4531 ) discrepant</td>
</tr>
<tr>
<td>-0.5</td>
<td>1.5 - 3.5</td>
<td>Good</td>
</tr>
<tr>
<td>-1.0</td>
<td>&gt;4.0</td>
<td>Good</td>
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</table>

Table 5
Carbon Abundance Estimates for NGC 330/B10

<table>
<thead>
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<th>[A/H]</th>
<th>( v_{\text{TURB}} )</th>
<th>[C/A]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.5</td>
<td>-0.6 ± 0.2</td>
<td>FeI ( \lambda 4325 ) prediction too strong</td>
</tr>
<tr>
<td>-0.5</td>
<td>2.5</td>
<td>-0.6 ± 0.2</td>
<td>FeI ( \lambda 4325 ) prediction too strong</td>
</tr>
<tr>
<td>-1.0</td>
<td>4.5</td>
<td>-0.6 ± 0.2</td>
<td>FeI ( \lambda 4325 ) prediction too strong</td>
</tr>
</tbody>
</table>
insensitive to heavy element abundance and microturbulence changes. The ratios of the three features at $\lambda\lambda 4527, 4529, 4531$ are now microturbulence indicators.

The optimum abundance/microturbulence pairs for NGC 330/B10 are listed in Table 4 and displayed in Figure 4. A similar heavy element abundance as in NGC 330/B20 (i.e., $-0.5 \leq [A/H] \leq -1.0$) is indicated for this star; a solar heavy element abundance gives a poor fit to the $\lambda 4541$ feature and the $\lambda\lambda 4527, 4529, 4531$ ratios indicate that the optimum microturbulence for solar abundance is too low.

Carbon abundances for NGC 330/B10 are listed in Table 5 and spectra for the upper and lower limits on the carbon abundances are compared with the observed C band spectrum in Figure 4. Carbon abundances slightly lower than found for NGC 330/B20 are indicated. The poor agreement with the FeI $\lambda 4325$ line in Figure 4 for $[A/H] = 0.0$ and $-0.5$ suggest that the heavy element abundance in NGC 330/B10 may be as low as $[A/H] = -1.0$. This result is also indicated from the fits to the $\lambda 4541$ feature.

NGC 330/B40: NGC 330/B40 has similar atmospheric parameters to NGC 330/B10 so Figure 3 is applicable to both stars. Only the 4500 - 4600Å region of NGC 330/B40 is compared with theoretical predictions (Fig. 5). A heavy element abundance of $[A/H] = -0.5$ is suggested for this star from the general fit to the whole $\lambda 4541$ feature (Table 6).

(iii) **LMC Abundances**

The atmospheric parameters listed in Table 1 for the remaining supergiants differ in surface gravity by only a small amount. Since the sensitivity to surface gravity differences is small, we compare each of these spectra with predictions for models with $T_e/\log g = 3800/0.3$. 
FIG. 5 - Comparison of observed and computed spectra for NGC 330/B40. The heavy line in each frame is the spectrum of NGC 330/B40. Model spectra (light lines) are for Te/\log g = 3950/0.35 and [A/H]/\nu_{TURB} parameters as marked in each frame. Spectral features discussed in the text are indicated.
Table 6

Consistent Abundance/Microturbulence Pairs

for NGC 330/B40

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>$v_{turb}$</th>
<th>Quality of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.5 - 3.5</td>
<td>Fair: $\lambda 4541$ and $\lambda \lambda 4527, 4529, 4531$ discrepant</td>
</tr>
<tr>
<td>-0.5</td>
<td>2.5 - 4.5</td>
<td>Fair - Good</td>
</tr>
<tr>
<td>-1.0</td>
<td>&gt;5.5</td>
<td>Fair: $\lambda 4541$ prediction too weak</td>
</tr>
</tbody>
</table>
The sensitivities to changes in the atmospheric parameters for these models are shown in Figure 6. The features in both regions are now stronger but their sensitivity to each parameter is qualitatively similar to that in Figure 3.

**NGC 2100/Cl2:** Estimated heavy element abundance/microturbulence pairs for this star are listed in Table 7 and the spectra are compared in Figure 7. Once again a heavy element abundance of \([A/H]=-0.5\) is indicated from the general fit to the whole \(\lambda 4541\) feature. A carbon abundance of the same order as found for the SMC supergiants is also indicated (Table 8, Fig. 7).

**NGC 2004/Cl4:** Estimated heavy element abundance/microturbulence combinations for NGC 2004/Cl4 are listed in Table 9 and the spectra are presented in Figure 8. The spectra for different heavy element abundances can not be distinguished on the basis of the fit to the \(\lambda 4541\) feature. The microturbulence sensitive features \(\lambda 4527, 4529, 4531\) indicate that the optimum microturbulence for solar abundance is too low. This fact suggests that NGC 2004/Cl4 does not have solar heavy element abundance. Carbon abundances of the same order as found above are also indicated for NGC 2004/Cl4 (Table 10, Fig. 8).

(iv) **Galactic Supergiant Abundances**

**CD -57° 3346:** This star is the M1.5 Iab-Ib supergiant in the galactic open cluster NGC 3293. Abundance/microturbulence pairs for this star are listed in Table 11 and the spectra are compared in Figure 9. It is not possible to distinguish between the \([A/H]=0.0\) and \(-0.5\) spectra on the basis of the fits to their \(\lambda 4541\) and \(\lambda 4527, 4529, 4531\) features. The poor fit to the \(\lambda 4541\) feature for \([A/H]=-1.0\) allows us to exclude
FIG. 6 - Sensitivities of the computed spectra to changes in the atmospheric parameters for parameters appropriate to the galactic and LMC supergiants. The light line in each frame is the spectrum for $T_e$/log g/[A/H]/$v_{TURB} = 3800/0.5/-0.5/2$. From top to bottom, the heavy line in each frame is the spectrum for 3600/0.5/-0.5/2, 3800/-0.5/-0.5/2, 3800/0.5/0.0/2, 3800/0.5/-0.5/4. Spectral features discussed in the text are indicated.
FIG. 7 - Comparison of observed and computed spectra for NGC 2100/Cl2. The heavy line in each frame is the spectrum of NGC 2100/Cl2. Model spectra (light lines) are for $T_e/\log g = 3800/0.3$ and $[\text{A/H}]/v_{\text{TURB}}$ parameters as marked in the right-hand portions of each frame. G band spectra are computed for these parameters and the upper and lower carbon abundance limits listed in Table 8. Spectral features discussed in the text are indicated.
Table 7
Consistent Abundance/Microturbulence Pairs for NGC 2100/Cl2

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>$v_{TURB}$</th>
<th>Quality of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.5 - 3.5</td>
<td>Fair: $\lambda$4541 too strong, $\lambda\lambda$4527, 4529, 4531 discrepant</td>
</tr>
<tr>
<td>-0.5</td>
<td>2.0 - 4.0</td>
<td>Fair</td>
</tr>
<tr>
<td>-1.0</td>
<td>4.0</td>
<td>Fair: $\lambda$4541 blend too weak</td>
</tr>
</tbody>
</table>

Table 8
Carbon Abundance Estimates for NGC 2100/Cl2

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>$v_{TURB}$</th>
<th>[C/A]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.5</td>
<td>$-0.8 \pm 0.2$</td>
<td>FeI $\lambda$4325 prediction too strong</td>
</tr>
<tr>
<td>-0.5</td>
<td>3.0</td>
<td>$-0.6 \pm 0.2$</td>
<td>-</td>
</tr>
<tr>
<td>-1.0</td>
<td>4.5</td>
<td>$-0.4 \pm 0.2$</td>
<td>Good Match</td>
</tr>
</tbody>
</table>
FIG. 8 - Comparison of observed and computed spectra for NGC 2004/C14. The heavy line in each frame is the spectrum of NGC 2004/C14. Model spectra (light lines) are for $T_e$/log $g = 3800/0.3$ and [A/H]/$v_{TURB}$ parameters as marked in the right-hand portion of each frame. G band spectra are computed for these parameters and the upper and lower carbon abundance limits listed in Table 10. Spectral features discussed in the text are indicated.
### Table 9
Consistent Abundance/Microturbulence Pairs for NGC 2004/C14

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>v$_{TURB}$</th>
<th>Quality of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0 - 2.5</td>
<td>Fair</td>
</tr>
<tr>
<td>-0.5</td>
<td>2.0 - 4.0</td>
<td>Fair</td>
</tr>
<tr>
<td>-1.0</td>
<td>&gt;4.5</td>
<td>Fair</td>
</tr>
</tbody>
</table>

### Table 10
Carbon Abundance Estimates for NGC 2004/C14

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>v$_{TURB}$</th>
<th>[C/A]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.5</td>
<td>-0.6 ± 0.2</td>
<td>Fei λ4325 prediction too strong</td>
</tr>
<tr>
<td>-0.5</td>
<td>3.0</td>
<td>-0.6 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>-1.0</td>
<td>5.0</td>
<td>-0.4 ± 0.2</td>
<td>-</td>
</tr>
</tbody>
</table>
FIG. 9 - Comparison of observed and computed spectra for CD $-57^\circ$ 3346. The heavy line in each frame is the spectrum of CD $-57^\circ$ 3346. Model spectra (light lines) are for $T_e$/log $g = 3800/0.3$ and $[\text{A/H}]_{\nu_{\text{TURB}}}$ parameters as marked in the right-hand portion of each frame. G band spectra are computed for these parameters and the upper and lower carbon abundance limits listed in Table 12. Spectral features discussed in the text are indicated.
Table 11
Consistent Abundance/Microturbulence Pairs for CD -57° 3346

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>(v_{\text{TURB}})</th>
<th>Quality of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.5 - 3.5</td>
<td>Good</td>
</tr>
<tr>
<td>-0.5</td>
<td>2.5 - 4.5</td>
<td>Good</td>
</tr>
<tr>
<td>-1.0</td>
<td>&gt; 5.0</td>
<td>Fair: 4541 prediction too weak</td>
</tr>
</tbody>
</table>

Table 12
Carbon Abundance Estimates for CD -57° 3346

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>(v_{\text{TURB}})</th>
<th>[C/A]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.5</td>
<td>-0.8 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>-0.5</td>
<td>3.5</td>
<td>-0.6 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>-1.0</td>
<td>5.5</td>
<td>-0.6 ± 0.2</td>
<td>-</td>
</tr>
</tbody>
</table>
FIG. 10 - Comparison of observed and computed spectra for CD -60° 3621. The heavy line in each frame is the spectrum of CD -60° 3621. Model spectra (light lines) are for Te/ log g = 3800/0.3 and [A/H]/v_TURB parameters as marked in the right-hand portion of each frame. G band spectra are computed for these parameters and the upper and lower carbon abundance limits listed in Table 14. Spectral features discussed in the text are indicated.
### Table 13

**Consistent Abundance/Microturbulence Pairs**

for CD $-60^\circ$ 3621

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>$v_{\text{TURB}}$</th>
<th>Quality of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0 - 3.0</td>
<td>-</td>
</tr>
<tr>
<td>-0.5</td>
<td>2.0 - 4.0</td>
<td>-</td>
</tr>
<tr>
<td>-1.0</td>
<td>$&gt;4.5$</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 14

**Carbon Abundance Estimates for CD $-60^\circ$ 3621**

<table>
<thead>
<tr>
<th>[A/H]</th>
<th>$v_{\text{TURB}}$</th>
<th>[C/A]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.0</td>
<td>$-0.8 \pm 0.2$</td>
<td>-</td>
</tr>
<tr>
<td>-0.5</td>
<td>3.0</td>
<td>$-0.8 \pm 0.2$</td>
<td>-</td>
</tr>
<tr>
<td>-1.0</td>
<td>5.0</td>
<td>$-0.6 \pm 0.2$</td>
<td>-</td>
</tr>
</tbody>
</table>
this possibility for CD $-57^\circ$ 3346. Similar carbon abundances to those derived for the LMC and SMC supergiants are indicated for CD $-57^\circ$ 3346 (Table 12, Fig. 9).

CD $-60^\circ$ 3621: CD $-60^\circ$ 3621 is one of two almost identical early M supergiants in the galactic open cluster NGC 3766. Abundance/microturbulence pairs for this star are listed in Table 13 and the spectra are presented in Figure 10. $[A/H] \geq -0.5$ is indicated from the appearance of these spectra. Carbon abundances are listed in Table 14 and are again similar to those derived above for the LMC and SMC supergiants.

IV. DISCUSSION

The seven Magellanic Cloud and galactic stars analysed here form part of a larger sample of late-type supergiants from these galaxies for which broad band infrared photometry, 2.3 $\mu$m CO indices, and TiO band strength data have previously been measured and analysed (MH2, McGregor 1981a, b). The bluer H-K colours of the Magellanic Cloud supergiants were shown to be indicative of these stars being deficient in CN (by a factor of -3 for the LMC stars) relative to similar galactic stars. The weaker 2.3 $\mu$m CO indices for the LMC supergiants compared with the galactic stars were interpreted as due to lower overall abundances ($[A/H] \approx -0.5$) in the LMC stars. The 2.3 $\mu$m CO indices for the NGC 330 (SMC) supergiants were found to be weaker than predicted for an overall metallicity of $[A/H] = -1.0$ and three possibilities were suggested to explain their observed CO indices; (1) the heavy element abundance could be normal for the SMC (i.e., $[A/H] = -1.0$) but these stars could be carbon deficient ($[C/A] = -0.5$), (2) these stars could be deficient in heavy elements by a factor of -30 ($[A/H] = -1.5$), (3) the microturbulent velocities in the NGC 330
supergiants could be significantly lower than in similar galactic supergiants. The TiO band strengths indicated a mean metallicity of \([A/H] \approx -0.5\) for the LMC supergiants and \([A/H] \leq -0.5\) for the SMC supergiants. Carbon abundance estimates have now been obtained from the G band spectra of a small number of these stars and further low precision estimates of the heavy element abundances have been made. These new estimates are summarized in Table 15.

(a) **Heavy Element Abundances**

The heavy element abundance estimates made in this paper are not of high accuracy. However, they are broadly consistent with those expected for Population I stars in each galaxy (e.g., van den Bergh 1975), and with the heavy element abundances estimated from the observed TiO band strengths for these stars. The spectrum of NGC 330/B20 is inconsistent with that star having a metallicity of \([A/H] \approx -1.5\). Although not demonstrated here, the same result appears likely for the other NGC 330 supergiants from the appearance of their spectra. This possible explanation of the small 2.3 \(\mu\)m CO indices for the NGC 330 supergiants can therefore be rejected. The low precision of the heavy element abundance determinations limits the precision with which we can assign microturbulent velocities to each star.

(b) **Carbon Abundance**

Since the derived C/A ratios for each star are essentially independent of the adopted heavy element abundances (Tables 2 - 14) and the synthetic spectra show the CH features to be largely independent of the other atmospheric parameters, the C/A ratios derived here are considerably more certain than the heavy element abundances discussed above. It can be seen from Table 15 that, *differentially*, the galactic and Magellanic Cloud stars have very similar carbon abundances. The uncertainties in
Table 15

Summary of Heavy Element and Carbon Abundances

<table>
<thead>
<tr>
<th></th>
<th>[A/H]</th>
<th>v\text{\textsubscript{TURB}}</th>
<th>[C/A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 330/B20</td>
<td>-0.5</td>
<td>2.5 - 4.5</td>
<td>-0.4 ± 0.3</td>
</tr>
<tr>
<td>NGC 330/B10</td>
<td>-0.5 - -1.0</td>
<td>2.0 - 4.5</td>
<td>-0.6 ± 0.3</td>
</tr>
<tr>
<td>NGC 330/B40</td>
<td>-0.5</td>
<td>2.5 - 4.5</td>
<td>-</td>
</tr>
<tr>
<td>LMC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 2100/C12</td>
<td>-0.5</td>
<td>2.0 - 4.0</td>
<td>-0.6 ± 0.3</td>
</tr>
<tr>
<td>NGC 2004/C14</td>
<td>0.0 - -1.0</td>
<td>2.0 - 5.0</td>
<td>-0.6 ± 0.3</td>
</tr>
<tr>
<td>GALACTIC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD -57° 3346</td>
<td>0.0 - -0.5</td>
<td>1.5 - 4.5</td>
<td>-0.6 ± 0.3</td>
</tr>
<tr>
<td>CD -60° 3621</td>
<td>0.0 - -0.5</td>
<td>1.5 - 4.0</td>
<td>-0.8 ± 0.3</td>
</tr>
</tbody>
</table>

The abundance values are related to the statistical uncertainties in the observed spectra. The uncertainties are indicated in the table. The abundance values for each galaxy are expected to be in the range [C/A] = -0.8 ± 0.3.
the differential carbon abundances are largely due to the statistical uncertainties in the observed spectra and are estimated to be $\pm 0.2$ dex from consideration of the numbers of counts in the G band region of each spectrum and of the sensitivities of the CH features to abundance. Thus, within this uncertainty, the same carbon abundance is derived for each star.

That the deficiencies relative to solar as listed in Table 15 are also accurate is supported by two factors. First, the same G band region line list and synthetic spectrum code have been shown previously to give reasonable spectra for α Boo, for the Sun, and for two Hyades giants for the expected carbon abundances of these stars (Cottrell and Norris 1978). Thus absolute carbon abundances derived from this code are expected to be of reasonable accuracy. Second, Luck (1978) has measured carbon abundances in 16 galactic G and K supergiants from the [CI] line at $\lambda$8727.13 and found that, in the mean, carbon is deficient by $0.53 \pm 0.12$ dex relative to the Sun in these stars. This mean galactic supergiant carbon abundance is in good agreement with the values listed in Table 15 for our supergiants. Thus the G band spectra indicate that all the Magellanic Cloud and galactic supergiants studied in this paper are deficient in carbon by the same factor of $-0.6$ dex. The fits to the observed G band spectra limit the accuracy of these carbon abundance determinations to $\pm 0.2$ dex. When we also include the probable statistical uncertainty in the observed spectra (which was not considered in §III), the uncertainty in the individual carbon abundance estimates increases to $\pm 0.3$ dex. Thus the mean carbon abundances for supergiants in our samples from each galaxy are expected to all lie in the range $[C/A] = -0.6 \pm 0.2$. 
(c) **Comparison with Other Indicators**

Carbon deficiencies of $[C/A] = -0.5$ were suggested previously (McGregor 1981a) as a possible explanation of the small 2.3 $\mu$m CO indices for the NGC 330 supergiants. However, the implication in that paper was that such carbon deficiencies were not also applicable to the galactic and LMC stars. When taken together, the heavy element abundances, carbon abundances, and microturbulent velocities derived in this paper are difficult to reconcile with the measured CO indices for the Magellanic Cloud stars. A reappraisal of the chemical abundances in the Magellanic Cloud supergiants is therefore necessary.

Mean heavy element abundances of $[A/H] = -0.5$ and $-0.5$ to $-1.0$ seem reasonably secure for the LMC and SMC supergiants, respectively. The LMC result is indicated from the results of this paper, from the mean TiO band strengths for the stars in our LMC sample (McGregor 1981b) and from the mean relation formed by these stars in the $(CO)_o$ vs $(J-K)_o$ plane (McGregor 1981a). This result is also consistent with the results from abundance studies of other Population I objects in the LMC. Judging from the small scatter of most of these stars in the $(CO)_o$ vs $(J-K)_o$ plane and from the larger scatter, but also greater sensitivity to abundance, in the TiO vs J-K plane, we estimate the uncertainty in the mean LMC abundance to be $\pm 0.2$ dex. This result assumes that the supergiants in our galactic sample have solar heavy element abundance.

The SMC result is based on the appearance of the blue spectra analysed in this paper (i.e., $[A/H]$ is considerably larger than $-1.5$ dex), and on the heavy element abundance limit (i.e., $[A/H] \leq -0.5$) set by the weakness of the TiO bands in the NGC 330 supergiants (McGregor 1981b). This result is also in agreement with other SMC abundance results (van den Bergh 1975).
Since the uniform carbon depletion suggested from the G band spectra is the strongest result of the present study, we will accept that this result is correct and attempt to find a consistent picture of the chemical abundances in the Magellanic Cloud supergiants within this framework. In addition, since the carbon deficiency we find is similar to that found for other galactic supergiants (Luck 1978), it seems reasonable to adopt the nitrogen and oxygen abundances found by Luck for these supergiants (i.e., [N/A] = +0.5, [O/A] = -0.3) as the probable nitrogen and oxygen abundances in the supergiants in our sample. Further calculations have shown that the effect of these different nitrogen and oxygen abundances on the G band analysis in §III is minimal.

Using the revised parameters, we have repeated part of our CO index analysis (McGregor 1981a) to determine whether the observed CO indices are consistent with this new picture. Model atmospheres for \( T_e = 4000K \) were taken from the grid of Johnson, Bernat and Krupp (1980) (supplemented with similar metal deficient models supplied by Dr. H.R. Johnson) and model atmospheres for \( T_e = 4500K \) were interpolated on the grid of Bell et al. (1976). In order to fit the mean galactic supergiant line in the \( (CO)_o \) vs \( (J-K)_o \) plane, we now require a mean microturbulent velocity for the galactic supergiants of \( 4.5 \pm 0.5 \) km sec\(^{-1}\). The fit to the LMC supergiant data using this velocity and \([A/H] = -0.5\) differs little from the match obtained previously. The fit to the NGC 330 supergiant data using a microturbulent velocity of \( 4.5 \) km sec\(^{-1}\) and a mean heavy element abundance of \([A/H] = -1.0\) is shown in Figure 11. The predicted indices are still significantly larger than the observed mean relation. Within the restrictions on the mean carbon abundance and the mean heavy element abundance (i.e., \([A/H] > -1.5\)) imposed in this paper, the only feasible explanation of the observed CO indices for the NGC 330 supergiants appears
FIG. 11 - (CO) vs (J-K) diagram showing the mean galactic (heavy solid) and SMC (heavy dashed) supergiant relations and theoretical CO indices for [C/A] = -0.5 and T_e/log g = 4000/1.0 and 4500/1.0, and [A/H]/v_{TURB} = 0.0/4.5, -1.0/4.5, and -1.0/2.5. Surface gravities along the mean galactic and SMC relations are indicated. The galactic relation is matched using v_{TURB} = 4.5 km sec^{-1}. v_{TURB} = 2.5 km sec^{-1} is required to fit the SMC relation.
to be that the mean microturbulent velocity for these stars is lower than
for the galactic supergiants. A mean microturbulent velocity of $2.5 \pm 0.5$
km sec$^{-1}$ is required to fit the observed NGC 330 CO indices using a mean
heavy element abundance of $[\text{A/H}] = -1.0$. This value is just within the
large uncertainties in the microturbulent velocities for the NGC 330
supergiants found in §III(b). If a larger mean heavy element abundance
is used, a lower mean microturbulent velocity is required to fit the
mean NGC 330 CO relation.

V. CONCLUSIONS

Intermediate resolution blue spectra in the region of the G band
for five Magellanic Cloud and two galactic late-type supergiants have
been analysed in this paper using a spectrum synthesis approach. The
strongest result of the present analysis is that, based on their G band
spectra, all seven of the supergiants in this study have similar carbon
to heavy element abundance ratios which are lower, on average, by
$0.6 \pm 0.2$ dex than the solar value (Lambert 1978).

The overall heavy element abundances obtained by attempting to fit
the 4500 - 4600Å region spectra provide support, albeit of low precision,
for the mean heavy element abundances suggested from the TiO band strength
data and broad band infrared colours for these stars and are also consist-
ten with the heavy element abundances expected for Population I stars
in each galaxy. Heavy element abundances of $[\text{A/H}] = -1.5$ have been shown
to be unreasonably low for NGC 330/B20 and from the appearance of their
spectra it is likely that this same result also applies to the other
NGC 330 supergiants.
These new data and analyses force us to reject the two explanations of the lower 2.3 µm CO indices in the NGC 330 supergiants that were considered most likely; the NGC 330 supergiants apparently do not have carbon deficiencies greater than for similar galactic supergiants and their mean heavy element abundances are not likely to be as low as \([A/H] = -1.5\). Thus a reappraisal of the chemical abundances in the NGC 330 supergiants has been necessary. The most probable explanation of the small 2.3 µm CO indices of the NGC 330 supergiants now appears to be that they have mean heavy element abundances in the range \(-0.5 \leq [A/H] \leq -1.0\), they are depleted in carbon by \(0.6 \pm 0.2\) dex on average, and, if we assume that \([A/H] = -1.0\) and that they have nitrogen and oxygen abundances similar to galactic supergiants (Luck 1978), they have a mean microturbulent velocity of \(2.5 \pm 0.5\) km sec\(^{-1}\); lower than for galactic supergiants by \(-2\) km sec\(^{-1}\).

Based on their 2.3 µm CO indices, TiO band strengths and the results of the present analysis, the LMC supergiants appear to have a mean heavy element abundance of \([A/H] = -0.5 \pm 0.2\), a mean carbon depletion of \([C/A] = -0.6 \pm 0.2\) and a mean microturbulent velocity of \(4.5 \pm 0.5\) km sec\(^{-1}\).

High resolution spectroscopic analyses of early-type supergiants in the Magellanic Clouds have given results which suggest the existence of a considerable range in abundance amongst young Population I LMC stars (Przybylski 1979). Such a range in abundance is not suggested from HII region analyses (Pagel et al. 1978) or from Cepheid variable studies (Gascoigne 1980). In general the Magellanic Cloud supergiants in our sample form a tight relation in the \((CO)_0\) vs \((J-K)_0\) plane, indicating a low CO abundance dispersion. The scatter of LMC supergiants in the TiO vs \((J-K)_0\) plane may be due to stellar variability and so can not be cited as evidence for an abundance spread amongst the supergiants in our sample.
Thus we can find no convincing evidence in our data for the existence of
general, large-scale abundance variations in the LMC or SMC stars. Never­
theless, NGC 2004/C14 does lie consistently above, and NGC 2100/D16 does
lie consistently below the mean LMC relations in both the CO vs J-K and
TiO vs J-K diagrams by considerable amounts. Thus the abundances of these
two stars may differ significantly from the mean LMC supergiant abundances.
These results suggest that if significant abundance variations exist
among Population I LMC supergiants, they are restricted to only a small
percentage of these stars.

Decisive determinations of the microturbulent velocities in our
program stars are clearly required before further progress can be made
towards a completely satisfactory picture of the chemical abundances in
Magellanic Cloud late-type supergiants. The blue spectra used here are
heavily blended and so are not suited to determining microturbulent
velocities from individual lines. High resolution red spectra would be
better suited to this task and should be obtainable using large telescopes
and red sensitive photon counting detector systems which are now available.

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I would especially like to thank Dr. A.R. Hyland for the advice and
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grateful to Drs. B. Gustafsson and H.R. Johnson for permitting the use
of unpublished model atmospheres. I thank Drs. A.R. Hyland and J.E. Norris
for their comments and criticisms of the manuscript. I acknowledge the
support of an Australian Commonwealth Postgraduate Research Award.
APPENDIX

LATE-TYPE SUPERGIANT BLUE SPECTRA
REFERENCES


CONCLUSIONS

In this thesis, an attempt has been made to define the observational differences between Magellanic Cloud and galactic late-type supergiants and to use these differences to infer a consistent picture of the chemical abundances in the Magellanic Cloud stars. In the course of this work an understanding of the evolutionary status of the supergiants in our sample and some insight into the star formation history of the 30 Doradus region have also been obtained. I will now briefly retrace the path taken in this research and summarize its major conclusions.

Observational Characteristics

The observational properties of late-type supergiants in the central region of the 30 Doradus complex (Chapter 2) and in young Magellanic Cloud blue globular clusters (Chapter 3) have been investigated. The following differences between the observed properties of these stars and those of similar galactic supergiants have been identified.

(1) The broad band infrared colours of the Magellanic Cloud supergiants are both redder in (J-H)_o and bluer in (H-K)_o than for galactic supergiants of the same luminosity.

(2) The 2.3 μm CO indices for the LMC and NGC 330 (SMC) supergiants are smaller by ~0.04 and ~0.1 mag, respectively, than for galactic supergiants of the same (J-K)_o colour. The 30 Doradus supergiants form an especially tight relation in the (CO)_o vs (J-K)_o plane, below and parallel to the mean galactic supergiant line.

(3) The TiO band strengths of the Magellanic Cloud supergiants are weaker than the band strengths of galactic supergiants of the same (J-K)_o colour.
(4) For \((J-K)_0\) colours greater than \(-1.0\) mag, the \((V-K)_0\) colours of the Magellanic Cloud supergiants are bluer than for galactic supergiants of the same \((J-K)_0\) colour. This difference was identified as being due to the effect on the \(V\) magnitude of the weaker TiO bands in the metal deficient Magellanic Cloud stars (Chapter 3). The existence of this \(V-K\) colour difference for stars with effective temperatures below \(-3800K\) suggests that caution is required in using \((V-K)_0\) as a temperature indicator in cool metal deficient stars when the \(T_e\) vs \((V-K)_0\) calibration is based, on stars of solar abundance.

Thus it is now apparent that Magellanic Cloud and galactic late-type supergiants can be distinguished by the differences in their infrared and optical properties. Various theoretical analyses have been used to quantify the physical and chemical differences responsible for these observational differences.

**Physical and Chemical Characteristics**

Model atmosphere broad band infrared colour calculations have been used to show that the CN molecular opacity is important in determining the positions of late-type supergiants in the \((J-H)_0\) vs \((H-K)_0\) plane (Chapter 2). The greater CN blanketing in high luminosity late-type stars, predominantly in the region of the \(H^-\) ion opacity minimum (i.e., the H pass band), was shown to be responsible for the separation between luminosity class Ia and Ib supergiants in the \((J-H)_0\) vs \((H-K)_0\) plane in each galaxy. The existence of this separation has been known for many years but its origin had not previously been explicitly associated with the CN molecular opacity. In contrast, the effect on J-K of substantial changes in the CN band strength was shown to be small, thus demonstrating the value of J-K as a temperature indicator in metal deficient late-type stars.
The weaker CN absorption in metal deficient supergiants was shown to make \((J-H)_o\) redder and \((H-K)_o\) bluer than in solar abundance stars of the same luminosity. Thus the observed differences in the broad band infrared colours of Magellanic Cloud and galactic supergiants have been interpreted as due to the effects of metal deficiency on the CN opacity in the Magellanic Cloud supergiants. An overall metal abundance deficiency for the LMC supergiants of a factor of -3 was shown to be consistent with their broad band infrared colours. The broad band colours of the hotter NGC 330 (SMC) supergiants are displaced from those of galactic supergiants in the same sense as for the LMC stars, thus indicating that these SMC stars are also deficient in CN relative to galactic supergiants, although a precise estimate of this deficiency could not be made.

A synthetic spectrum analysis of the 2.3 \(\mu\)m CO bands in late-type supergiants has been successfully used to obtain quantitative abundance information from the observed CO index data (Chapter 4). The strong sensitivity of the CO index to microturbulent velocity complicates the analysis. This difficulty was initially circumvented, however, by assuming that the mean microturbulent velocities of supergiants in each galaxy are the same. Using this assumption, the 2.3 \(\mu\)m CO indices for the LMC supergiants were found to be consistent with an overall metal abundance deficiency of \([A/H] = -0.5\) in these stars, in agreement with the CN deficiency estimated from broad band infrared data and with published abundance determinations for other LMC Population I objects. No CNO abundance anomalies, relative to the galactic supergiants, were required to interpret the observed CO indices of the LMC supergiants.

An overall heavy element abundance of \([A/H] = -1.0\) was expected for the NGC 330 (SMC) supergiants from published abundance determinations for other Population I objects in the SMC. However, the CO indices for
the NGC 330 supergiants are weaker than predicted using this heavy element abundance and the microturbulence assumed above. Three possibilities have been suggested to explain the smaller observed CO band strengths in these stars: (1) the heavy element abundances in the NGC 330 supergiants could be typical of the SMC (i.e., \([A/H] = -1.0\)) and the C/A ratios could be lower by ~0.5 dex relative to similar galactic supergiants, (2) the heavy element abundance could be as low as \([A/H] = -1.5\), (3) the heavy element abundance could be typical of the SMC (i.e., \([A/H] = -1.0\)) but the mean microturbulent velocity of the NGC 330 supergiants could be considerably lower than for the galactic supergiants.

A synthetic spectrum approach has also been used with recently published cool supergiant model atmospheres to analyse the observed TiO band strengths (Chapter 5). Encouraging agreement with the observed TiO band strengths for galactic stars was obtained in this analysis. This fact suggests that the quantitative TiO abundances estimated for the Magellanic Cloud supergiants are also of reasonable accuracy. A mean abundance deficiency of \([A/H] = -0.5\) was again inferred for the LMC supergiants, this time from their measured TiO band strengths. However, considerable scatter exists at constant \((J-K)_0\) colour in the TiO band strengths for the LMC supergiants and it is not clear whether this scatter is due to real band strength differences between individual LMC supergiants or to stellar variability since the TiO spectra and infrared photometry were not obtained concurrently. An upper limit of \([A/H] \leq -0.5\) was placed on the NGC 330 supergiant abundances from the weakness of the TiO bands in these stars. This limit is consistent with other indicators of the heavy element abundances in these stars.
Independent abundance estimates for a few supergiants have also been obtained from analysis of intermediate resolution blue spectra in the region of the G band (Chapter 6). These analyses permit a clarification of the carbon abundances in the Magellanic Cloud stars and enable the abundance alternatives for the NGC 330 supergiants suggested from the 2.3 µm CO index analyses to be distinguished. Heavy element abundance estimates from these spectra are of low accuracy but are again consistent with results from other indicators (i.e., [A/H] = -0.5 for the LMC stars and -0.5 < [A/H] < -1.0 for the SMC stars). Analysis of the CH features in the G band indicates that carbon is depleted uniformly relative to the heavy elements by [C/A] = -0.6 ± 0.2 in all the supergiants subjected to detailed analysis. By analogy with the similar mean carbon deficiency known to be present in other galactic G and K supergiants, it is expected that nitrogen may also be enhanced by -0.5 dex and oxygen depleted by -0.3 dex in the supergiants in this study.

Using these revised abundances, the fit to the measured 2.3 µm CO index data requires that the mean microturbulent velocities of the galactic and LMC supergiant samples must both be equal to 4.5 ± 0.5 km sec^{-1}. For the NGC 330 supergiants, the possibility that [A/H] = -1.5 can be excluded from the appearance of their blue spectra and the possibility of a greater carbon depletion in the NGC 330 supergiants than in the galactic supergiants is contradicted by the result of uniform carbon abundances from the G band analyses. Thus in order to fit the measured 2.3 µm CO indices for the NGC 330 supergiants with the abundances inferred from the G band analysis, and with the low value of [A/H] = -1.0, it appears that we require the mean microturbulent velocity for the NGC 330 supergiants to be 2.5 ± 0.5 km sec^{-1} (i.e., ~2 km sec^{-1} lower than for the LMC and galactic supergiants). If a higher abundance is assumed, an even lower microturbulent velocity is required. The reality of this difference in mean microturbulent velocity is unclear at the present time.
Thus the mean chemical abundances for the Magellanic Cloud supergiants that result from this analysis are $[\text{A/H}] = -0.5 \pm 0.2$, $[\text{C/A}] = -0.6 \pm 0.2$ for the LMC supergiants and $-0.5 \lesssim [\text{A/H}] \lesssim -1.0$, $[\text{C/A}] = -0.6 \pm 0.2$ for the SMC supergiants. These abundances are entirely consistent with other estimates of the chemical abundances in young Population I Magellanic Cloud objects, if we accept that nuclear processed material has been mixed to the stellar surface in these late-type supergiants.

A final comment on abundances relates to the dispersion in abundance about these mean values. In the Introduction (Chapter 1), it was noted that a spread in young Population I abundances in the LMC was suggested from the large range in abundance obtained from high-resolution spectroscopic analyses of luminous early-type supergiants, while at the same time the colours of Magellanic Cloud Cepheid variables appeared to severely restrict the size of any abundance dispersion amongst these stars, and HII region abundance results showed no evidence for a range in abundances. The sequences formed in the $(\text{CO})_o$ vs $(\text{J-K})_o$ plane by the supergiant samples from each galaxy studied in this thesis are fairly tight, indicating that the CO abundance dispersion is low, although a few stars do lie off the mean LMC relation by amounts which are larger than the expected observational errors. As noted in Chapter 5 and above, a large scatter does exist in the TiO band strengths reported for the LMC supergiants. However, this scatter may be due to variability in the LMC stars between the epochs at which their TiO spectra and infrared photometry were obtained and so this scatter cannot be unambiguously ascribed to an abundance spread.

A very few of the stars studied in this thesis, such as NGC 2004/C14, do lie consistently off the mean relations by a considerable amount and in the same sense in both the CO and TiO diagrams and may thus have different
abundances from the bulk of the stars studied in this thesis. Thus it appears that the dispersions in the abundances of the LMC and SMC supergiants studied in this thesis are generally small, with only a very few stars possibly having significantly different abundances.

The absence of a definitive determination of the microturbulent velocities for the supergiants studied here remains a crucial problem which prevents an entirely satisfactory, complete picture of the chemical abundances in these stars being obtained. The lower mean microturbulent velocity inferred for the NGC 330 supergiants compared with the other supergiants was an unexpected result. Accurate determinations of the microturbulent velocities in the NGC 330 supergiants would allow this result to be checked directly and at the same time allow the carbon abundance result from the G band analysis to be tested since both these results must be correct in order to explain the measured CO indices of the NGC 330 supergiants in this way.

**Star Formation and Evolution**

The luminosities of the brightest main sequence stars in the blue globular clusters indicate end-main sequence masses of ~14 M☉ for each cluster (Chapter 3). The luminosities of the late-type supergiants in these blue globular clusters are generally consistent with expectations for core-carbon burning red supergiants of this mass, thus indicating that mass loss has probably not played a significant role in the evolution of these stars. However, the range in luminosity of stars on the giant branch of each cluster is larger than expected for core carbon burning supergiants having a unique mass and indicates that a spread of ~10⁷ yr exists in the formation times of the blue globular cluster stars. The
luminosity range of the 30 Doradus supergiants indicates that the older population in the 30 Doradus region formed over a time span of $\gtrsim 4 \times 10^6$ yr.

The 30 Doradus central cluster is very similar to the young blue globular clusters in the Magellanic Clouds. The presence of this compact cluster of massive Wolf-Rayet stars and other early-type stars in the midst of a larger association of older late-type supergiants indicates that at least two major bursts of star formation have occurred in this region in the last $\sim 5 \times 10^7$ yr; if star formation has continued through the interim period, it must have been at a significantly reduced rate. The presence of a slightly older, more extended stellar population in the same region of space appears to be a common characteristic of many Magellanic Cloud blue globular clusters. Thus it is tempting to speculate that the prior condensation of a more extended stellar association is a common feature of the formation of all globular clusters. Perhaps even all giant HII regions have globular clusters forming at their centres! If so, we would then also expect to find late-type supergiant stars associated with other extragalactic giant HII regions.

Further Research

(a) A problem remaining outstanding in this work is the question of the precise value of the microturbulent velocities in the Magellanic Cloud supergiants. The availability of new instrumentation has now made it possible to obtain high resolution red spectra of the Magellanic Cloud stars so that a more precise determination of the microturbulent velocities in these stars may be possible from an analysis of red spectral lines in comparatively unblended regions.
(b) Concurrent TiO band strength measurements and JHK photometry are required to determine the true range in TiO band strength at a given (J-K) colour for the LMC stars.

(c) A determination of the $^{12}\text{C}/^{13}\text{C}$ ratios in the Magellanic Cloud stars would be valuable in assessing the extent to which mixing processes have altered the initial chemical abundances of these stars. This ratio could be derived from the strengths of the 2.3 µm CO isotope bands using spectra obtained with "state of the art" infrared grating spectrometers.

(d) This thesis has demonstrated that differences exist in the infrared and optical properties of late-type supergiants in the Galaxy and the Large and Small Magellanic Clouds and that these observational differences can be successfully analysed to give quantitative chemical abundance information for the Magellanic Cloud stars. Late-type supergiants also occur in large numbers in other more distant galaxies in the Local Group and it should now be possible to obtain quantitative abundance information for these stars using a similar technique. An abundance analysis based on infrared molecular band strengths is ideally suited to the investigation of these distant stars since the flux distributions of late-type supergiants peak in the infrared region. Higher resolution spectroscopic analyses of these stars are not yet possible. M31, M33, NGC 6822 and IC 1613 have distance moduli in the range 24-25 mag and contain many red supergiants which are expected to have K magnitudes in the range 15-17 mag.

(e) Since late-type supergiants are part of an older stellar population which may have played an important role in the star formation history of the 30 Doradus region, it is now important to search for similar late-type supergiants in the vicinities of other giant HII regions in Local Group galaxies to determine whether their presence in such regions is a
general phenomenon. Absorption by the 2.3 μm CO bands in circular variable filter wheel spectra of these giant HII regions would indicate the presence of late-type supergiants in these systems.