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# M SUPERGIANTS IN LOCAL GROUP IRREGULAR GALAXIES: METALLICITIES AND DISTANCES

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## ABSTRACT

*JHK* photometry of confirmed and suspected red supergiants in NGC 3109, NGC 6822, IC 1613, Sextans A, and DDO 210 together with CO and $H_2O$ indices of some of the brighter stars has been done. The color and spectral type distributions in NGC 6822 and IC 1613 indicate that NGC 6822 is slightly more metal-rich than the Small Magellanic Cloud, while IC 1613 is more metal-poor. Sextans A is apparently comparable in metallicity to IC 1613, while NGC 3109 is probably comparable to the SMC. The absolute *K* magnitudes of the brightest red supergiants become brighter as the parent galaxy luminosity increases. The scatter about the mean relation is ~0.1 mag, allowing an estimate of 25.34 for the true distance modulus of NGC 3109. Comparison with data from Humphreys, Jones, and Sitko for the spiral galaxy M33 shows that it fits the irregular calibration less well.

*Subject headings:* galaxies: Local Group — galaxies: stellar content — stars: abundances — stars: late-type — stars: supergiants

## I. INTRODUCTION

Red supergiants in nearby galaxies are useful indicators of galaxian metallicity. In a comparison of the Milky Way and the Large and Small Magellanic Clouds, Humphreys (1979*b*) and Elias, Frogel, and Humphreys (1985, hereafter EFH) showed that the mean spectral types and colors of the red supergiants are sensitive to galaxian metallicity, in that the mean spectral type becomes earlier with decreasing metallicity, and mean intrinsic color at a given spectral type becomes (generally) bluer with decreasing metallicity. The two effects combine to produce a strong decrease in mean supergiant intrinsic color with decreasing metallicity.

The most luminous red stars in galaxies have also been considered useful as distance indicators. Extensive studies by Humphreys (1983, and references therein) and by Sandage and coworkers (Sandage and Tammann 1982; Sandage 1983*a*, *b*, 1984*a*, *b*) have shown that the *V* magnitudes of the brightest red supergiants are roughly constant for low-luminosity, irregular galaxies ($M \gtrsim -18$). Their absolute *V* magnitudes in more luminous galaxies are uncertain and may be brighter. Preliminary work in the infrared (Elias *et al.* 1981) showed that the absolute *K* magnitudes of these stars for less luminous galaxies were fainter than for more luminous galaxies; the bolometric luminosities showed a similar trend. The constancy of the absolute *V* magnitudes of the brightest red supergiants in irregular galaxies is thus apparently due to cancellation of two opposite effects: the brightest red supergiants are less luminous ($M_{\rm bol}$ or $M_K$) in less luminous galaxies, but their colors are bluer ($BC_V$ and $V-K$ are less).

In this paper, we report infrared photometry of candidate red supergiants in five nearby galaxies. In two—NGC 6822 and IC 1613—there are published spectral types for some of the stars as well as visual photometry (Humphreys 1980*a*, and references therein), and in one more—Sex A—there exists visual photometry (Sandage and Carlson 1982; Hoessel, Schommer, and Danielson 1983). For NGC 3109 and DDO 210 there is no published visual photometry.

For the three galaxies with visual photometry, we can compare the visual and infrared observations of the red stars with those for the Milky Way and Magellanic Clouds presented by EFH, after correction for foreground extinction, and produce a rough ordering by metallicity. A comparison with observations of M33 supergiants by Humphreys, Jones, and Sitko (1984) is also made. The results for NGC 6822, IC 1613, and M33 are consistent with other, more direct, metallicity estimates (Pagel and Edmunds 1981; Binette *et al.* 1982).

There are well-established distances from Cepheid photometry for the Magellanic Clouds and for NGC 6822, IC 1613, and Sex A; these can be combined with the infrared photometry to establish the relation between galaxy luminosity and the *K* magnitudes of the brightest red supergiants. The relation can be used to estimate the distance to NGC 3109 and should be applicable to other, similar galaxies where the red supergiants can be measured in the infrared.

## II. OBSERVATIONS AND RESULTS

### *a) Selection of Red Stars*

The five galaxies observed are listed in Table 1, together with some relevant properties. They are a subset of the nearby dwarf irregular galaxies accessible from the southern hemisphere for which we could identify candidate red supergiants. Some suitable galaxies (e.g., Sextans B, WLM) were not observed because of limited observing time. Also included are the Magellanic Clouds, which are used for comparison (see § III), and M33. Distances given are on the "infrared Cepheid" scale

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TABLE 1

PROPERTIES OF THE PROGRAM AND COMPARISON GALAXIES

| Galaxy | $A_V$[a] Foreground (mag) | $(m-M)_0$ Adopted | Area Surveyed (deg$^2$) | No. of Dwarfs[b] $V = 18$ | $V = 19$ |
|---|---|---|---|---|---|
| LMC | 0.11[c] | 18.48[d] | ... | ... | ... |
| SMC | 0.06[c] | 18.94[d] | ... | ... | ... |
| M33 | 0.09[e] | 24.06[d] | ... | ... | ... |
| NGC 6822 | 0.93[f] | 23.25[d] | 0.033 | 5 | 22 |
| IC 1613 | 0.04[g] | 24.31[d] | 0.06 | 7 | 14 |
| Sextans A | 0.05[h] | 25.43[i] | 0.004 | 0.6 | 1.2 |
| NGC 3109 | 0.12[h] | ... | 0.011 | 1.7 | 4.7 |
| DDO 210 | 0.11[h] | ... | 0.003 | 0.4 | 1.1 |

[a] Foreground extinction at $V$. At other wavelengths and colors, $A_K = 0.09A_V$; $E_{V-K} = 0.91A_V$; $E_{J-K} = 0.17A_V$; and $E_{H-K} = 0.06A_V$.
[b] Expected contamination by dwarfs with $M_V < +8.5$, see text.
[c] McNamara and Feltz 1980.
[d] Distances from IR photometry of Cepheids: McGonegal 1982; McGonegal *et al.* 1982; McAlary *et al.* 1983; McAlary *et al.* 1984; and McAlary, Madore, and Davis 1984.
[e] Sandage 1983*a*.
[f] Kayser 1967; Humphreys 1980*a*.
[g] Sandage 1971.
[h] Burstein and Heiles 1984.
[i] SC, revised (see text).

of Madore and coworkers (references in Table 1), adopting $m-M = 3.03$ for the Hyades.

The red stars to be observed were taken from the literature or from our own photographic surveys for red stars in these galaxies. For IC 1613 and NGC 6822 we observed most of the stars observed by Humphreys (1980*a*) plus seven additional NGC 6822 stars from Kayser (1966) and three additional IC 1613 stars from Sandage and Katem (1976).

For the remaining galaxies there were no published visual color-magnitude diagrams at the time this work was begun, so red stars were selected using matched $V$ and $I$ exposures taken at CTIO with the Yale 1 m telescope and image-tube camera. Plates were also taken of NGC 6822 as a test of the technique, and an even better test was provided by the publication of color-magnitude diagrams for Sex A by Sandage and Carlson (1982) and Hoessel, Schommer, and Danielson (1983) after the IR observations were made: the three brightest supergiants had been observed in the infrared (see Table 2).

For NGC 3109 and DDO 210 the identified red stars are shown in Figures 1 and 2; not all were observed in the infrared. For NGC 3109 only the brighter 16 stars are shown. The results on Sex A and NGC 6822 suggest that the red stars identified on the 1 m plates have $V-I$ (Johnson) $\gtrsim 1.8$ and $V \lesssim 19.5$.

### *b) LMC, SMC, and M33 Samples*

EFH reported observations of an extensive sample of stars in the LMC and SMC, which was probably reasonably complete for the most luminous stars. For the galaxies discussed here, the samples are less likely to be complete, which introduces biases into any comparison. In an attempt to reduce these biases, comparison samples of LMC and SMC stars were produced by selecting the 10 brightest stars from each galaxy, using observed visual magnitudes at the time of spectral classification, from Humphreys (1979*a*) and EFH, respectively. The LMC $V$ magnitudes were corrected following EFH. In the SMC, two stars tied for tenth place and were each given half-weight. The 21 stars are listed in Table 2.

Humphreys, Jones, and Sitko (1984) have done infrared photometry for red stars in M33; these results are also used in our analysis, together with visual photometry by Humphreys (1980*b*).

### *c) Photometry*

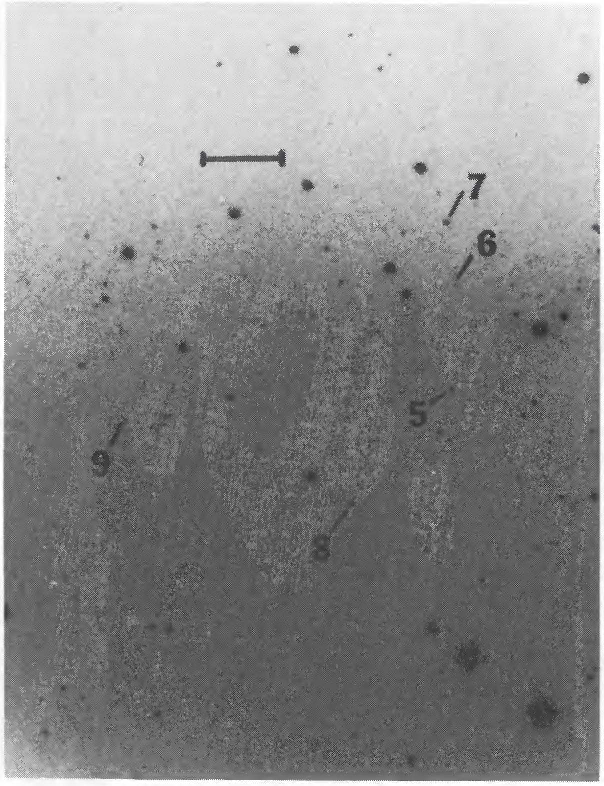
All observations were made on the CTIO 4 m telescope with the InSb detector during 1980 and 1981. The 1980 measure-

TABLE 2

BRIGHT-STAR SAMPLES IN THE MAGELLANIC CLOUDS

| Star | $V$ | $V-K$ | MK[a] |
|---|---|---|---|
| | LMC | | |
| Case 46-44 | 11.44 | 4.48 | M1 Ia |
| Case 46-32 | 11.61 | 4.31 | M0 Ia |
| Case 46-39 | 11.86 | 4.51 | M1 Ia |
| Case 53-3 | 12.04 | 4.27 | M0 Ia |
| Case 46-2 | 12.05 | 4.75 | M2 Ia |
| Case 46-33 | 12.06 | 4.42 | M0–1 Ia |
| Case 45-38 | 12.17 | 4.59 | M1 Ia |
| Case 52-17 | 12.21 | 4.59 | M1 Ia |
| Case 46-19 | 12.22 | 4.96 | M2 I + B |
| Case 46-39a | 12.23 | 4.15 | M1 Ia |
| | SMC | | |
| Case 107-1 | 11.34 | 3.76 | K5–M0 I |
| HV 11423 | 11.77 | 3.93 | M0 Ia |
| Case 120-14 | 11.96 | 3.78 | K5–M0 I |
| HV 1475 | 12.01 | 3.64 | K0–5 Ia |
| Case 118-5 | 12.02 | 3.28 | K5 Ia |
| Case 116-15 | 12.05 | 4.01 | M0 Ia |
| Case 118-15 | 12.07 | 4.18 | M0 I |
| Case 107-12 | 12.08 | 3.66 | M0 Iab |
| Case 106-1a | 12.24 | 4.34 | M0 Ia |
| Case 108-2[b] | 12.28 | 3.99 | M0 Ia–Iab |
| Case 107-7[b] | 12.28 | 3.92 | M0 Ia |

NOTE.—Stars selected on the basis of their apparent magnitude at time of spectral classification: see text for details.
[a] MK spectral type from Humphreys 1979*a* for LMC and EFH for SMC.
[b] Stars tied for tenth place; given half-weight each.



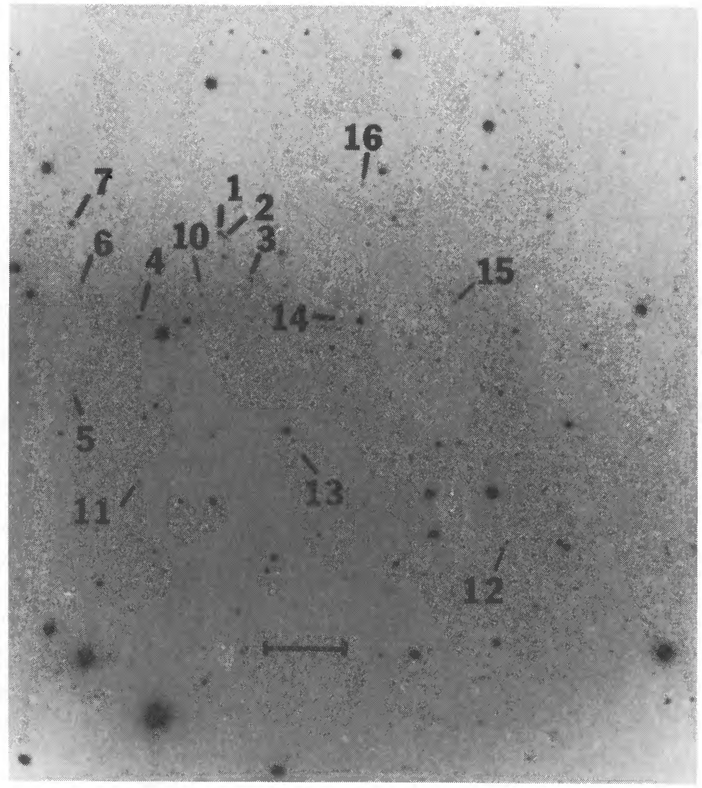




FIG. 1.—Identification of red stars in NGC 3109. North is at the top, and east is to the left; the horizontal bars are 1′. The charts are from an image-tube plate taken through an RG695 filter. The left-hand chart includes the eastern half of the galaxy, and the right-hand chart shows the remainder.

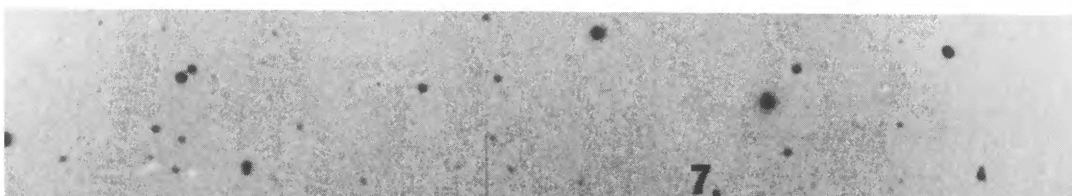



FIG. 2.—Identification of red stars in DDO 210. As in Fig. 1, except that a $V$ filter was used.

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TABLE 3

INFRARED PHOTOMETRY OF M SUPERGIANTS

| Star | Spectral Type[a] | K | J-K | H-K | $H_2O$ | CO | V-K | Remarks[d] |
|---|---|---|---|---|---|---|---|---|
| | | Observed Magnitudes and Colors[b] | | | | | | |
| NGC 6822 | | | | | | | | |
| V12 | M1I | 12.68(7) | 1.05(4) | 0.31(3) | 0.45(4) | 0.32(3) | 5.06 | sg,1,9 |
| V14 | M3-4 | 12.64(7) | 1.10(5) | 0.28(4) | 0.12 | 0.26(3) | 5.18 | sg,1,8 |
| V15 | cM | 13.09(8) | 1.02(5) | 0.30(4) | ... | ... | 4.88 | sg,1,9 |
| V18 | M1-2I | 12.18(5) | 1.00(5) | 0.24 | 0.15 | 0.25 | 4.87 | sg,1,8 |
| | | 12.23(3) | 1.08(3) | 0.25 | ... | ... | | 10 |
| V19 | M1I | 12.52(8) | 0.92(4) | 0.21(4) | ... | ... | 4.97 | sg,1,9 |
| V22 | ... | 12.88 | 1.12 | 0.26 | ... | ... | 6.16 | sg,1,10 |
| V23 | ... | 13.29 | 0.99 | 0.21 | ... | ... | 5.27 | sg,1,11 |
| B109 | ... | 13.20 | 1.06 | 0.24 | ... | ... | 5.00 | sg:,2,11 |
| B110 | M0I | 12.78(8) | 0.82(4) | 0.17(3) | 0.10(3) | 0.08(3) | 3.68 | sg,3,7,9 |
| C7 | ... | 13.76 | 1.00 | 0.21 | ... | ... | 4.06 | sg:,2 |
| C26 | M0-1I | 13.02 | 1.03 | 0.24 | ... | ... | 4.58 | sg,3,10 |
| C68 | ... | 12.80 | 1.03 | 0.24 | ... | ... | 5.04 | sg:,2,10 |
| C79 | M0-1I | 12.48(3) | 0.99(3) | 0.20 | ... | ... | 4.48 | sg,3,10 |
| D28 | ... | 13.11 | 1.18 | 0.29 | ... | ... | 4.95 | sg:,2,11 |
| D60 | ... | 13.44 | 1.07 | 0.22 | ... | ... | 4.60 | sg:,2,11 |
| E30 | ... | 14.18(3) | 0.87(3) | 0.16 | ... | ... | 3.76 | d:,3,11 |
| E38 | ... | 13.33 | 0.94 | 0.19 | ... | ... | 4.57 | 3,11 |
| IC 1613 | | | | | | | | |
| V19 | ... | 16.87(19) | 1.14(24) | 0.67(23) | ... | ... | 1.8: | sg,4,9 |
| V23 | ... | 14.56(4) | ... | ... | ... | ... | 3.51 | sg,3,11 |
| V32 | M1Ia | 13.12(8) | 0.87(4) | 0.22(4) | 0.07(3) | 0.26(3) | 4.05 | sg,3,9 |
| V38 | M0Ia | 13.12(5) | 0.64(5) | 0.18 | 0.05(3) | 0.31(4) | 3.84 | sg,3,8 |
| V43 | M1I | 14.44(6) | 0.77(6) | 0.19(4) | ... | ... | 3.02 | sg,3,7,8 |
| V45 | ... | 14.00 | 0.84 | 0.17 | ... | ... | 3.70 | sg,4,11 |
| V58 | ... | 14.10(8) | 0.84(6) | 0.16(5) | ... | ... | 3.45 | sg,3,9 |
| J48 | ... | 13.30 | 0.76 | 0.20 | ... | ... | 3.69 | d:,4,11 |
| Sextans A | | | | | | | | |
| 21 | ... | 14.57(4) | 0.93(5) | 0.24(4) | ... | ... | 3.74 | sg,5,10 |
| 39 | ... | 15.95(5)[c] | ... | ... | ... | ... | ... | 10 |
| 50 | ... | 14.70(4) | 0.74(5) | 0.09(4) | ... | ... | 3.55 | sg,5,10 |
| 56 | ... | 14.97(4) | 0.77(5) | 0.11(4) | ... | ... | 3.33 | sg,5,10 |
| PM2 | ... | 14.46(4) | 0.79(5) | 0.20(4) | ... | ... | 3.95 | d,6,10 |
| NGC 3109 | | | | | | | | |
| 1 | ... | 14.10(3) | 0.84(3) | 0.20(3) | ... | ... | ... | 10 |
| 3 | ... | 14.34(3) | 0.91(4) | 0.14(3) | ... | ... | ... | sg:,10 |
| 4 | ... | 14.65(3) | 0.76(4) | 0.15(4) | ... | ... | ... | 10 |
| 7 | ... | 13.72(3) | 0.75(4) | 0.27(3) | 0.21(4) | 0.00(4) | ... | d,10 |
| 11 | ... | 14.98(5) | 0.79(6) | 0.20(5) | ... | ... | ... | 10 |
| 12 | ... | 14.82(3) | 0.74(5) | 0.25(4) | ... | ... | ... | d:,10 |
| DDO 210 | | | | | | | | |
| 4 | ... | 16.26(7) | 0.87(10) | 0.19(7) | ... | ... | ... | 11 |
| 8 | ... | 15.18(3) | 0.81(4) | 0.23(3) | ... | ... | ... | d:,11 |

ments were affected by a loose field lens, which led to magnitudes (but not colors) of lower accuracy. The results are presented in Table 3; all magnitudes and colors are on the "CIT" system defined by Elias *et al.* (1982). Observations were made with diaphragms of between 7″ and 11″. The fields were examined at the telescope to make sure that nearby stars did not contaminate the signal or reference beams. Narrow-band CO and $H_2O$ indices were measured for only a few of the brightest stars. Also given are $V-K$ colors, where available. The accuracy of the individual $V-K$ colors is typically $\pm 0.2$ mag due to limitations of the photometry and variability of the stars. For NGC 6822 and IC 1613, the $V$ magnitudes are from Humphreys (1980*a*), Kayser (1966, 1967), and Sandage and Katem (1976). Identifications are from these references.

For Sextans A, there is photographic photometry by Sandage and Carlson (1982, hereafter SC) and CCD photometry by Hoessel, Schommer, and Danielson (1983, hereafter HSD). Unfortunately, the two data sets show substantial disagreements (HSD) in zero point and color. HSD observed in $g$ and $r$ (Thuan and Gunn 1976) and transformed to $V$ and $B-V$. If one excludes stars redder than $g-r = 0.5$ (roughly $B-V = 1.0$), the HSD and SC data sets show a zero-point difference of $\sim 0.2$ mag, in the sense that the HSD values are fainter. This may be due to the difficulties of extending SC's photoelectric sequence via a Racine wedge (see, e.g., Blanco 1982; Sandage 1984*a*). The magnitude difference appears to be similar for the comparison stars used by SC in measuring the Sextans A Cepheids. Any color terms are heavily influenced by the red stars in common between SC and HSD, most of which probably have $B-V \approx 1.5$. For stars this red, the transformations to the $B$, $V$ system from $g$, $r$ are probably much more uncertain than the transformations from SC's photographic $B$ and $V$ bandpasses. We have therefore produced magnitudes for the red supergiants by making the SC values fainter by 0.2 mag. For the foreground dwarf PM 2, where SC give no $V$ magnitude, the mean difference between the SC and HSD red star magnitudes was applied to the HSD $V$ magnitude, and it was then made fainter by 0.2 mag. These adopted $V$ magnitudes lie roughly midway between the HSD and SC values for the red stars. While we feel that the adopted values are the best available, systematic errors of 0.1 mag are quite likely, and additional visual photometry is clearly desirable. For the red stars, neither data set gives $B-V$ values which can be used with confidence. The apparent distance modulus from the Cepheids is changed to 25.43, where the changes are due to the effects of the zero-point shift and to a difference in the adopted distance and foreground reddening from the LMC, against which SC calibrated their Sex A data (Table 1). The identification numbers in Table 3 are from SC.

### *d*) *Membership*

It is possible to make estimates of the expected foreground star contamination for a given limiting color and magnitudes. The limiting (bluest) color implied by the observed $V-K$ colors (Table 3) is roughly $V-K = 3.5$, or $M_V = 8.7$ (Veeder 1974). Since the samples were visually selected, the appropriate limiting magnitude is $V$. Counts were computed from Bahcall and Soneira (1981) for stars with $M_V > +8.5$ down to $V = 18$ and 19. For each galaxy, the expected counts down to these limits in the area examined for red stars are given in Table 1. These counts are contributed almost entirely by stars in the disk, and the effects of a thick disk (Gilmore and Reid 1983) or a different spheroid density will be a few percent at most. The counts are much more sensitive to the adopted cutoff color; if it is decreased to $V-K = 3.0$, the counts increase by a factor of 1.5–2.5. Red giants will not contribute significantly to the counts in any case.

Identifications of the program stars as members or nonmembers—foreground dwarfs—are given in the last column of Table 3. Member stars are indicated by an "sg" or an "sg:" for definite and possible supergiants, respectively; foreground dwarfs are indicated by a "d" or a "d:". A number of stars could not be classified, and for these one can make only statistical arguments regarding membership.

A star is considered a definite member if it is a known variable or if a spectral classification is available. For a few stars, the narrow-band infrared photometry shows them to be supergiants or dwarfs. A star is considered to be foreground on the basis of spectral classification or proper motion.

One can use the broad-band infrared photometry to identify the late type supergiants and dwarfs, as shown in Figure 3. Here are shown the $J-H$, $H-K$ two-color diagrams for stars in Table 3 and Magellanic Cloud stars from Table 2; the values have been corrected for foreground (Milky Way) extinction (see Table 1) but not internal extinction. The dwarfs have also been corrected for the full foreground extinction, as they are likely to be quite distant (and the corrections are quite small in any case for all but NGC 6822).

It can be seen that most of the NGC 6822 stars with unknown membership, and NGC 3109-3, are almost certainly supergiants; these stars are marked "sg:" in Table 3. NGC 3109-12 and, with less certainty, IC 1613 J48 appear to be foreground dwarfs.

Of the remaining stars, in NGC 6822, E30 is already suspect-

NOTES TO TABLE 3

[a] Spectral types from Humphreys 1980*a*, except for NGC 6822 V14, which is from Humphreys 1984.
[b] Uncertainties in percent are shown in parentheses, unless less than 2%.
[c] $H$ magnitude.
[d] REMARKS.—sg, sg:, d, and d: indicate confirmed and probable supergiants and confirmed and probable foreground dwarfs, as discussed in the text.
(1) $V$ magnitudes are mean values from Kayser 1967.
(2) $V$ magnitudes from Kayser 1966.
(3) $V$ magnitudes from Humphreys 1980*a*.
(4) $V$ magnitudes from Sandage and Katem 1976.
(5) $V$ magnitudes from SC, corrected as discussed in text.
(6) $V$ magnitude from HSD, corrected as discussed in text.
(7) Anomalously blue colors, star included in Table 4 averages.
(8) IR photometry done 1980 September.
(9) IR photometry done 1980 October.
(10) IR photometry done 1981 March.
(11) IR photometry done 1981 July.

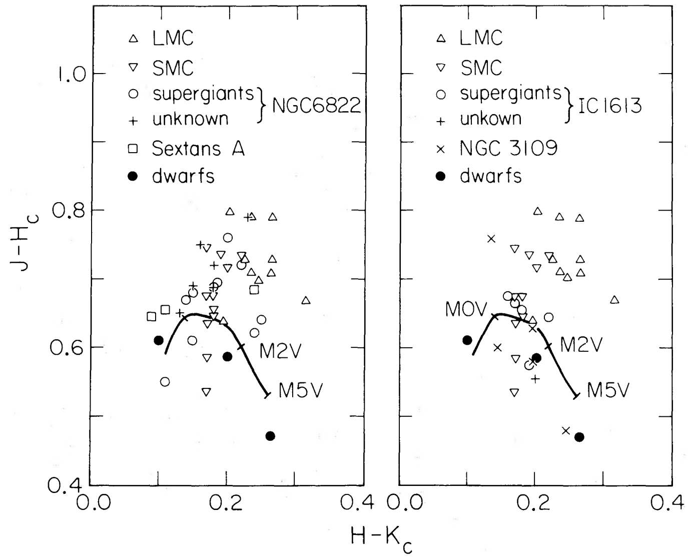


FIG. 3.—$J-H$ vs. $H-K$ colors for stars in Tables 2 and 3, corrected for foreground extinction. The mean line for dwarfs with $V-K$ between 3 and 5 is shown, taken from Frogel *et al.* (1978). The LMC and SMC data are repeated in both panels, as are the data for the three confirmed dwarfs from Table 2. Stars in Sextans A and NGC 6822 are plotted in the left-hand panel, and stars in IC 1613 and NGC 3109 are plotted in the right-hand panel.

ed as a foreground star (Humphreys 1980*a*), and it is possible that another one or two of the stars in Table 3 is foreground (most likely E38). The bulk of the stars come from the inner 60% of Kayser's field and have $V-K$ typically 4 or larger. The number of foreground stars in this smaller sample is expected to be $\sim 1$.

For IC 1613, the stars observed are all known variables and hence members, except J48, whose colors identify it as a probable dwarf. Judging from Table 1, many of the nonvariable red stars in Sandage and Katem (1976) are likely to be dwarfs. V19 is clearly a member, but its rather blue $V-K$ color and considerable variability (Sandage 1971) suggest it may not be a normal M supergiant. It has therefore been left out from the analyses presented below.

For Sex A the small area of the galaxy reduces the contamination. Of the stars in Table 3, only SC 39 has unknown membership. Its estimated $V-K$ color is rather blue—less than 3—and it is statistically likely to be a foreground star.

For NGC 3109, the limiting magnitude for the stars observed is probably between 18 and 19. Stars 7 and 12 are probably both dwarfs, and statistics suggest $\sim 1$ other should be a dwarf—most likely star 11. Star 7 has strong $H_2O$, which confirms it as a dwarf.

Finally, for DDO 210, the observations are so limited that there is little to be said. It is plausible that the two stars in Table 3 are both foreground. Certainly DDO 210 does not have a population of red supergiants comparable to that in Sex A, which implies that it either is more distant or has no red supergiants.

## III. DISCUSSION

### *a) Metallicity*

In EFH, it was shown that the mean intrinsic colors and spectral type distributions of the M supergiants in the Milky Way, LMC, and SMC are related to their metallicity. In this section, the procedure is reversed: using the observed properties of the supergiants, we discuss the metallicity of the program galaxies. For two—NGC 6822 and IC 1613—there are limited data on the metallicity (Lequeux *et al.* 1979; Binette *et al.* 1982) which indicate that NGC 6822 is slightly more metal-rich than the SMC, and that IC 1613 is slightly more metal-poor, but with considerable uncertainties. M33 is dealt with separately (§ III*c*).

Spectral types exist only for NGC 6822 and IC 1613 stars. In NGC 6822 the mean type is M1, while in IC 1613 the mean (from three stars) is M0–1. In the LMC the mean spectral type is M1, while the SMC it is slightly earlier than M0. There is, however, a bias present in that the NGC 6822 and IC 1613 stars with spectra are predominantly known variables, which biases the mean spectral type toward later type (EFH). The mean spectral type of LMC supergiant Harvard variables is near M2, while for the SMC it is uncertain but later than M0 (EFH). Since the mean spectral type of the four NGC 6822 variables is $\sim$M2, this suggests that NGC 6822 has almost the same metallicity as the LMC. The metallicity of IC 1613 is difficult to assess but appears to be less than that of the LMC and probably comparable to or slightly greater than that of the SMC.

The analysis in EFH involved the dereddening of the individual stars, based on intrinsic colors derived for each galaxy. For the present study, this is not possible, as the data are of lower accuracy and the samples are smaller. Instead, a somewhat different approach has been adopted. It is possible to make estimates of foreground extinction for all the galaxies (Table 1); these are probably accurate to $\pm 0.1$ in $A_V$, or better. The resulting mean colors for supergiants are then mean intrinsic colors plus internal extinction. These are listed in Table 4.

Examination of these values indicates that the corrected colors of the supergiants in all four galaxies are distinctly bluer than those of the LMC and are comparable to those of the SMC. In detail, it appears that in NGC 6822 the stars have slightly redder colors than in the SMC, and that in IC 1613 and Sex A the stars have marginally bluer colors than in the SMC. This suggests that NGC 3109, NGC 6822, IC 1613, and Sex A all have metallicity similar to that of the SMC, with NGC 6822 being slightly more metal-rich and IC 1613 and Sex A being slightly more metal-poor.

TABLE 4

MEAN SUPERGIANT PROPERTIES

| GALAXY | MEAN CORRECTED COLORS[a] | | | ABSOLUTE $K$ MAGNITUDES[b] | | | |
|---|---|---|---|---|---|---|---|
| | $V-K$ | $J-K$ | $H-K$ | $M_{K,1}$ | $M_{K,3}$ | $M^*_{K,3}$ | $M_G$[c] |
| LMC ................ | 4.40 | 0.98 | 0.25 | −11.53 | −11.32 | −11.29 | −18.06 |
| SMC ................ | 3.80 | 0.84 | 0.18 | −11.37 | −11.18 | −11.08 | −16.46 |
| M33 ................ | 4.06 | 0.91 | 0.23 | −11.58 | −11.13 | −11.13 | −18.08 |
| NGC 6822 .......... | 4.00 | 0.87 | 0.19 | −11.13 | −10.93 | −10.84 | −15.16 |
| IC 1613 ............ | 3.56 | 0.83 | 0.18 | −11.19 | −10.90 | −10.75 | −14.40 |
| Sextans A ........... | 3.49 | 0.80 | 0.14 | −10.87 | −10.69 | −10.69 | −13.70 |
| NGC 3109[d] ......... | ... | 0.82 | 0.16 | −11.26 | −10.99 | ... | −15.69 |

[a] Mean colors corrected for foreground extinction, for confirmed or probable supergiants only. See text.

[b] $M_{K,1}$ is the brightest supergiant $K$ magnitude for each galaxy from Tables 2 and 3 and HJS; $M_{K,3}$ is mean of the three brightest $K$ magnitudes; and $M^*_{K,3}$ is the mean $K$ magnitude for the three visually brightest stars. *Note that $M_{K,1}$ and $M_{K,3}$ for larger samples in the SMC and LMC are brighter, especially in the LMC.* See text for details and discussion.

[c] Absolute total $B$ magnitude of galaxy corrected for foreground extinction and inclination. See text.

[d] NGC 3109 absolute magnitudes use true distance modulus of 25.34, as derived in text.

This use of mean colors to determine metallicity assumes that the mean internal extinction does not vary dramatically among the dwarf irregular galaxies. If NGC 6822 were more metal-poor than the SMC, its mean internal visual extinction would have to be at least 0.7 mag. (The mean $A_V$ for the SMC found by EFH is ~0.4 mag.) The apparently most metal-poor galaxies could be made significantly more metal-rich than the SMC only if their internal extinction were negligible. Estimates of internal extinction for early-type stars in NGC 6822 and IC 1613 by Humphreys (1980*a*) suggests that the internal extinction for both galaxies is comparable to that in the SMC.

There are differences in the mean internal extinction between the galaxies due to different orientations. Corrections for the individual galaxies to convert observed magnitudes to face-on magnitudes can be computed following the RC2 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976); these corrections are presumably primarily due to the effects of different internal absorptions due to different orientations. These corrections are less than 0.1 mag in $B$ for all of the galaxies with supergiants except for the SMC and NGC 3109. For the SMC, the correction corresponds to ~0.16 mag in $V-K$, and for NGC 3109 it is ~0.37 mag, while for the four other galaxies it is ~0.03 mag. If these corrections are appropriate, NGC 6822 lies still more definitely between the SMC and LMC, while NGC 3109, IC 1613, and Sex A have colors essentially the same as in the SMC.

The need for orientation corrections, and their uncertain magnitude, illustrates the limitations of the technique: differences in mean $V-K$ less than 0.2 mag may not be significant.

Estimates of the total blue luminosities of the program galaxies ($M_G$) are also given in Table 4. It is clear that the ordering of the galaxies in metallicity does not exactly reflect their ordering in luminosity. NGC 6822 is decidedly less luminous than the SMC, but its metallicity is almost certainly higher. Also, there seems to be little separation in metallicity between the SMC and lower luminosity galaxies like Sex A and IC 1613, whereas the smaller difference in luminosity between the SMC and LMC corresponds to a rather substantial metallicity difference. A similar trend and scatter are seen in the abundances of larger samples of irregular galaxies (e.g., Kunth and Sargent 1983, and references therein).

Some confirmation of metallicity estimates based on supergiant colors could be provided by additional spectroscopy of the stars in these irregular galaxies. Specifically, a more complete sample of NGC 6822 stars should show a greater proportion of M0 supergiants, while the red, nonvariable IC 1613 stars which are not foreground dwarfs should be predominantly M0 or later-K supergiants. The Sex A stars and the NGC 3109 stars should also be M0 or earlier.

Narrow-band CO and $H_2O$ indices were measured only for a few bright supergiants in NGC 6822 and IC 1613 and for the foreground dwarf NGC 3109-7. The NGC 6822 values are compatible with a metallicity midway between that of the SMC and LMC, but the IC 1613 CO indices are large for a metallicity no greater than that of the SMC—from the SMC results in EFH, one would expect CO indices nearer 0.22, although individual SMC stars do have CO indices as strong as 0.30, and the uncertainties of the IC 1613 measures are large.

### *b) Brightest Stars and the Distance to NGC 3109*

An earlier paper (Elias *et al.* 1981, hereafter EFHP) showed that infrared photometry of M supergiants, by itself, does not provide reliable distances to galaxies because the stellar $K$ magnitude depends on galaxian luminosity. The relevant data for the program galaxies are summarized in Table 4. These values differ somewhat from those in EFHP because slightly different distance moduli have been used, because there are now IR data for V45 in IC 1613, and because there is no correction for internal extinction in Table 4. The fundamental differences discussed in EFHP are preserved though—the LMC stars are somewhat more luminous at $K$ than the SMC stars, while the IC1613 and NGC 6822 stars are fainter, as are the Sex A stars.[2]

If one plots the absolute magnitude of the brightest (at $K$) supergiant (taken from the samples in Tables 2 and 3), corrected for foreground reddening, $M_{K,1}$, against galaxy absolute magnitude, a reasonably good linear fit results, with a slope of 0.13 (Fig. 4); a similar fit with reduced scatter is produced if the mean corrected absolute magnitude of the three stars brightest at $K$, $M_{K,3}$, is used (Fig. 4). The luminosity function of the M supergiants in these galaxies is steep but not discontinuous; for

[2] If the SC photometric zero point for Sex A were used, the absolute $K$ magnitudes would be still fainter by 0.2 mag, which leaves a rather large difference between the Sex A $K$ magnitudes and the IC 1613 $K$ magnitudes, given the relatively small difference in absolute magnitude.

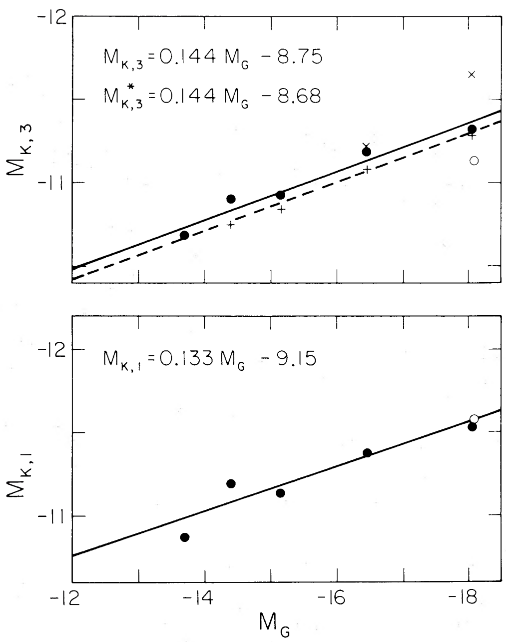


FIG. 4.—Absolute $K$ magnitudes of M supergiants from Tables 2 and 3 plotted against corrected galaxy absolute blue magnitude. The bottom panel shows as filled circles the brightest $K$ magnitude ($M_{K,1}$), and the top panel shows the mean of the brightest three $K$ magnitudes ($M_{K,3}$). The × symbols show the means for the three brightest K magnitudes in the much larger sample of LMC and SMC stars observed by EFH. The plusses show the mean $K$ magnitudes of the three visually brightest stars in each galaxy ($M^*_{K,3}$); for Sextans A, $M^*_{K,3}$ is the same as $M_{K,3}$. The solid lines are the fits of $M_{K,1}$, and $M_{K,3}$ vs. $M_G$, and the dashed line is the fit to $M^*_{K,3}$. The open circles are $M_{K,1}$ and $M^*_{K,3}$ ($= M_{K,3}$) for M33 from HJS; these were not used in the fits.

less luminous galaxies there are fewer supergiants, and the brightest (or three brightest) supergiants are likely on the average to be fainter. One can see from Figure 4 that the average $K$ magnitude of the three brightest supergiants is about the same as that of the brightest supergiant in a galaxy 3 times less luminous. Within the accuracy of the relation, this must be true also for the bolometric magnitudes, since the bolometric correction to the $K$ magnitude is fairly insensitive to modest changes in metallicity and spectral type (EFH).

For the calibration of $M_{K,1}$ and $M_{K,3}$ in Figure 4, the stars which are brightest at $K$ have been selected from the stars in Tables 2 and 3, which are the brightest stars at $V$. This is a somewhat arbitrary definition, and it is worth asking how altering the selection criteria affects the calibration, since the stars which are visually brightest are not always the same as the stars which are brightest in the infrared.

If one takes *all* the M supergiants in a galaxy and selects those brightest at $K$, there are rather substantial effects. From the work of EFH, it is known that there are two LMC stars (MG 46 and Case 29-33 [HV 888]) which are brighter at $K$ than any of the LMC stars in Table 2; inclusion of these makes $M_{K,3}$ brighter by 0.33 mag. In the SMC there is a weaker effect, in that HV 2084, which is not in Table 2, becomes the second brightest star, and $M_{K,3}$ is made brighter by 0.04 mag. In NGC 6822, where the sample of stars is relatively large, the three stars brightest at $K$ are included in the five visually brightest stars, which suggests that the effect of a still larger sample on $M_{K,3}$ would be small. The color-magnitude diagrams of IC 1613 and Sex A are so sparse that it also seems unlikely that there are visually faint stars which are more luminous at $K$ than those measured. The plot of $M_{K,3}$ for complete samples will therefore have a steeper slope (by about 50%). There will be a somewhat smaller effect on $M_{K,1}$. The difficulty in obtaining a truly complete sample in the infrared, independent of visual identifications, limits the utility of $M_{K,3}$ or $M_{K,1}$ as distance indicators.

Conversely, we can ask what happens if one considers only the three stars brightest in $V$ and takes their mean $K$ magnitude, $M^*_{K,3}$ (Table 4). Since the samples in Tables 2 and 3 are so small, it is not surprising that the effect is rather small—the line in Figure 4 is shifted fainter by ~0.07 mag, without a significant change in slope.

The differences in the selection criteria and their effect on the resulting calibration serve to illustrate the potential systematic errors. It is clear, for example, that any extrapolation to galaxies more luminous than the LMC is hazardous without additional calibrating galaxies.

If one assumes that stars 1, 3, and 4 are members of NGC 3109, then the calibrations for $M_{K,1}$ or $M_{K,3}$ can be used to determine a distance. Without visual photometry, the $M^*_{K,3}$ calibration cannot be used. If the $M_{K,1}$ and $M_{K,3}$ calibrations are given equal weight, then the resulting true distance modulus of NGC 3109 is 25.34, and its total blue magnitude is $-15.69$. The formal uncertainties are less than $\pm 0.1$ mag in the distance modulus, but the assumptions involved in the method are not adequately tested by a calibrating sample of five galaxies, nor have the three stars been confirmed as members.

It seems that the most effective application of infrared photometry of red supergiants to determine distances requires that the red supergiants be identified and their $V$ magnitudes measured. $K$ magnitudes can then be measured for the three visually brightest stars to determine $M^*_{K,3}$. The resulting accuracy in the relative distances for irregular galaxies with $M_G$ between $-14$ and $-18$ is formally $\pm 0.1$ mag. The preparatory visual work is already enough to provide distances of $\pm 0.2$ mag accuracy using the $V$ magnitudes as calibrators (e.g., Sandage and Tammann 1982; Humphreys 1983), although the method may not be reliable for more luminous galaxies (cf. Sandage 1983*a*, *b*, 1984*a*, *b*).

Use of the infrared magnitudes of red supergiants to find distances does not require very exact knowledge of the galaxy total magnitude: an uncertainty of $\pm 0.5$ mag in $B^0_T$ leads to an uncertainty of slightly less than $\pm 0.1$ mag in $(m - M)_0$. Formally, if $m^*_{K,3}$ is the mean $K$ magnitude of the three visually brightest stars, corrected for foreground extinction, and $B^0_T$ is the total $B$ magnitude of the galaxy, corrected for inclination and foreground extinction (following RC2, except that $A_B$ is taken from Burstein and Heiles 1984), then

$$(m - M)_0 = 1.168 m^*_{K,3} + 10.30 - 0.168 B^0_T \, . \qquad (1)$$

### *c) M33*

Humphreys, Jones, and Sitko (1984, hereafter HJS) have presented infrared data and a summary of visual data for a sample of red supergiants in M33, including the three visually brightest red stars. Mean corrected colors (on the CIT system) formed in the same way as for the other program galaxies are given in Table 4. Since the HJS stars are all spectroscopically identified as supergiants, there is no problem with contamination. On the basis of the mean colors, the M33 supergiants should be roughly midway in metallicity between those in the LMC and SMC.

Humphreys (1980*b*) gives spectral types for five red supergiants in M33; these range from M0 to M3, with a mean of M1–2. This spectral type distribution implies an average metallicity similar to that of the LMC. The color and spectral type data together are thus consistent with an average metal abundance slightly less than that in the LMC. M33 is known to have a significant abundance gradient, unlike (so far as is known) the other galaxies in the sample (Smith 1975; Dopita, D'Odorico, and Benvenuti 1980; Kwitter and Aller 1981). At the distances from the center of M33 of the red supergiants observed by HJS, the abundances are roughly comparable to (or less than) those in the LMC. The mean colors in Table 4 imply that M33 is slightly more metal-rich than NGC 6822, which is consistent with other abundance indicators. Corrections for orientation, such as those discussed above (§ III*a*), do not alter the estimate of M33's metallicity significantly.

The distance to M33 $[(m-M)_0 = 24.06]$ in Table 1 and the absolute magnitudes given in Table 4 are taken from the "infrared Cepheid" distance scale of Madore and collaborators. Sandage (1983*a*) has derived a rather larger distance estimate. If Sandage's distance scale is adjusted, for purposes of comparison, so that his LMC apparent blue modulus is the same as that implied by Table 1 (18.59; cf. SC), his true modulus for M33 becomes $(m-M)_0 = 24.81$. All absolute magnitudes would thus be made brighter by $\sim$0.75 mag. Either distance estimate causes $M^*_{K,3}$ to depart from the irregular calibration line by a large amount. If one applies equation (1) to the observed $M^*_{K,3}$ and $B^0_T$ for M33, a distance modulus of 24.40 results. This is about 2 standard deviations away from both the McAlary *et al.* (1984) and the Sandage (1983*a*) values. However, in M33 it is quite possible that there are additional M supergiants at least as bright visually as those observed by HJS. If so, the true value of $m^*_{K,3}$ would probably be brighter, and the distance derived from equation (1) would be smaller. In any case, the distance determination is valid only if the luminosity function for red supergiants, normalized to galaxy blue luminosity, is the same in M33 as in the irregular galaxies which define the calibration. A factor of 3 change in the relative number of bright red supergiants would shift the derived distance by $\sim$0.2 mag.

## IV. CONCLUSIONS

There are two principal results of this study. First, visual and infrared photometry of the red supergiants in nearby galaxies can be used to estimate galaxian metallicity. The technique has been demonstrated for galaxies with $M_G \gtrsim -18$ and remains to be tested for more luminous galaxies. The Milky Way is a rather difficult object to include as a calibrator, because we observe it from a privileged position.

Similarly, while the $K$ magnitudes of the brightest supergiants can probably be used as distance indicators, there is a dependence of their magnitudes on the luminosity of the parent galaxy; the size of the effect is not known for galaxies more luminous than the LMC.

Because the sample of calibrating galaxies is so small, the effects of galaxian metallicity and luminosity on the brightest supergiants' magnitudes cannot be separated. This needs to be done, especially if one wants to consider the relative merits of magnitudes at other wavelengths (e.g., $V$) as calibrators, since if $K$ is a good calibration wavelength, $V$ magnitudes will give distances which are systematically too distant for anomalously metal-rich galaxies and systematically too close for anomalously metal-poor galaxies. Examination of the data for M33 does not show whether the calibration derived for irregular galaxies is accurate for spiral galaxies.

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