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Globular clusters and the Mira period–luminosity relation

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ABSTRACT

A globular cluster distance scale based on *Hipparcos* parallaxes of subdwarfs has been used to derive estimates of M_K for cluster Miras, including one in the Small Magellanic Cloud (SMC) globular cluster NGC 121. These lead to a zero-point of the Mira infrared period–luminosity (PL) relation, PL(K), in good agreement with that derived from *Hipparcos* parallaxes of nearby field Miras. The mean of these two estimates together with data on LMC Miras yields a Large Magellanic Cloud (LMC) distance modulus of 18.60 ± 0.10 in evident agreement with a metallicity-corrected Cepheid modulus ($18.59 \pm \sim 0.10$).

The use of luminous asymptotic giant branch (AGB) stars as extragalactic population indicators is also discussed.

Key words: stars: AGB and post-AGB – stars: variables: other – globular clusters: general – distance scale.

1 INTRODUCTION

That Mira variables show a good infrared period-luminosity relation was established from Large Magellanic Cloud (LMC) observations (Glass & Lloyd Evans 1981; Glass & Feast 1982; Feast 1984; Feast et al. 1989). In particular, Feast et al. (1989) showed from multi-epoch photometry that the average absolute magnitude at K (2.2μm) had a rather small scatter (0.13 mag) for oxygen-rich Miras from the relation,

$$M_K = -3.47 \log P + \gamma. \quad (1)$$

More recent work (Whitelock & Feast 2000a; also in preparation) shows that in the LMC the bolometric PL relation extends up to at least ~1500 d. Menzies & Whitelock (1985) obtained multi-epoch *JHK* photometry of a number of Miras in galactic globular clusters and showed that they could be fitted to a PL relation, though offset from that of the LMC, on the basis of the then current distance scale of the clusters and of the LMC. Whitelock et al. (1994) showed that the LMC Miras and those in galactic globular clusters fitted the same PL relations if the cluster distance scale were fixed by LMC globular clusters and an assumed LMC distance. These workers also included Miras with distances known in other ways (i.e. Miras with companions of known luminosity). Recently a Mira PL zero-point was obtained from local Miras with *Hipparcos* parallaxes (Whitelock & Feast 2000b). In the present paper we derive and discuss an independent Mira PL zero-point based on Miras in globular clusters. This is now possible using a cluster distance scale set via the *Hipparcos* parallaxes of subdwarfs (Carretta et al. 2000 and references there). We also give infrared photometry for the Mira V1 in the Small Magellanic Cloud (SMC) globular cluster NGC 121 and include it in the analysis. This is the only Mira with a known period in a globular cluster (and hence with an estimated metallicity) outside our Galaxy, although long-period carbon Miras are known in intermediate-age Magellanic Cloud clusters (Nishida et al. 2000).

2 DATA

The basic data used in this paper are listed in Table 1. The K magnitudes listed are (except in the case of one star, see Section 2.7) the means of maximum and minimum of Fourier fits to the available data sets. The latter are mainly from Menzies & Whitelock (1985) but referred to Carter (1990) standards (see Appendix). In the case of the three variables in 47 Tuc, the multi-epoch photometry of Frogel, Persson & Cohen (1981) was included.

The *JHK* observations of NGC 121 V1 are given in Table 2. These were obtained with the MkIII infrared photometer on the 1.9-m reflector at SAAO, Sutherland.[1] The uncertainties in these measures are 0.05 mag except for those on JD 244 5949 when they are ~0.08 mag. Carretta et al. (2000) have rediscussed the distances of globular clusters based on subdwarf parallaxes from *Hipparcos*. On the basis of this they then derive (their equation 3) a

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Table 1. Data on Miras in globular clusters.

Mira	[Fe/H]	$E(B-V)$	V_{ZAHB}	$(m-M)_0$	K	$(J-K)$	$\log P$	M_K	Note
N104 V1	−0.67	0.055		13.38	6.20	1.28	2.326	−7.20	1
V2					6.30	1.16	2.307	−7.05	
V3					6.33	1.28	2.283	−7.07	
N121 V1	−1.02			19.09	12.39	0.94	2.147	−6.71	2
N5139 V42		0.15		13.77	7.41	1.13	2.174	−6.40	3
N5927 V3	−0.46	0.47	16.72	14.55	7.25	1.49	2.491	−7.43	
N6352 L36	−0.64	0.21	15.30	13.96	7.20	1.25	2.243	−6.82	
N6356 V3	−0.64	0.24		16.20	9.02	1.30	2.342	−7.24	4
V4					8.99	1.36	2.316	−7.27	
V5					9.02	1.39	2.342	−7.24	
N6553 V4	−0.50	0.63		14.08	6.32	1.59	2.423	−7.93	5
″	−0.44	0.84	16.92	13.60				−7.51	
N6637 V4	−0.68	0.17	15.95	14.74	7.96	1.24	2.292	−6.83	
N6712 V7	−0.88	0.46	16.32	14.25	7.44	1.36	2.280	−6.93	
N6838 V1	−0.70	0.25	14.52	13.07	6.29	1.29	2.286	−6.85	
Ter 5 V_S	0.00	2.49		14.17	7.73	2.30	2.356	−7.11	6
V					6.62	2.44	2.389	−8.22	

Notes: 1 – distance modulus from subdwarfs (see text); 2 – $A_V = 0.10$, $V(\mathrm{HB}) = 19.69$; 3 – see text for distance modulus and reddening; 4 – $V(\mathrm{HB}) = 17.50$; 5 – [Fe/H], $E(B-V)$ and V(HB) from Zoccali et al. (2001b), see text; 6 – [Fe/H], $E(B-V)$ and V(HB) from Ortolani et al. (1996), see text.

relation between the zero-age horizontal branch (ZAHB) absolute magnitude and the cluster metallicity, viz:

$$M_V(\mathrm{ZAHB}) = 0.18([\mathrm{Fe/H}] + 1.5) + 0.53. \quad (2)$$

They also derive (their equation 2),

$$M_V(\mathrm{HB}) = 0.13([\mathrm{Fe/H}] + 1.5) + 0.44 \quad (3)$$

for the mean level of the horizontal branch (HB). Unless otherwise stated we have used equation (2) above to derive the distance moduli of the clusters. The values of $E(B-V)$, [Fe/H] and V_{ZAHB} used are given in the table. They were taken from Ferraro et al. (1999). The values of [Fe/H] are on the scale of Carretta & Gratton (1997). We have adopted a value of $R = A_V/E(B-V) = 3.1$, (see below). The periods are generally those quoted by Menzies & Whitelock (1985) from the literature. That for L36 in NGC 6352 is from Whitelock (1986). The following comments are on specific clusters.

2.1 NGC 104 (47 Tuc)

The adopted distance modulus is that derived directly from subdwarf fitting by Carretta et al. (2000). The reddening and metallicity are also from that paper. Zoccali et al. (2001a) derive a distance modulus for 47 Tuc from a white dwarf cooling sequence, which is 0.28 mag nearer than the one used here. However, they indicate that there are a number of problems to be solved before such a distance is fully reliable.

Table 2. Infrared observations of NGC 121 V1. (ΔJD = JD − 2440000.)

ΔJD	J	H	K
5577	12.90	12.24	12.09
5603	13.19	12.38	12.20
5604	13.22	12.33	12.15
5621	13.54	12.55	12.40
5647	13.70	13.06	12.75
5652	13.72	12.97	12.80
5688	13.42	12.37	12.64
5949	13.47	13.04	12.70
5953	13.47	12.84	12.64
6042	13.40	12.58	12.34
6090	13.37	12.73	12.49
6100	13.34	12.68	12.54
6113	13.10	12.33	12.22
6394	13.18	12.38	12.19

2.2 NGC 121

The distance was derived from the data of Dolphin et al. (2001). Their adopted metallicity and visual absorption were used together with their value of V(HB) and equation (3), above. This would appear to be the correct procedure rather than using the ZAHB relation as Dolphin et al. did (A. Walker, private communication). The distance modulus finally adopted by Dolphin et al. is 0.13 mag less than our value. This depends on comparing the colour–magnitude diagram with a theoretical model. In the present paper it seemed best to use the HB result to be consistent with the other clusters and to avoid using theoretical models.

2.3 NGC 5927

The cluster membership of the Mira V3 in this cluster has not been firmly established from radial velocities, although it is near the centre of the cluster. The period (the longest of any Mira in a globular cluster) seems well determined (Andrews et al. 1974). The distance modulus must be considered uncertain because the metallicity of the cluster is greater than that of any of the clusters used to establish equation (2), the most metal-rich of which is 47 Tuc. It should be noted, in particular, that there is some evidence from RR Lyrae variables that the M_V(HB) and M_V(ZAHB) relations (equations 2 and 3) may steepen at high metallicities (see e.g. Caputo et al. 2000 and references therein).

2.4 NGC 6356

The basic data for this cluster are taken from Bica, Ortolani & Barbuy (1994) with the cluster metallicity converted to the Carretta–Gratton scale using equation (7) of Carretta & Gratton

(1997). As in the case of NGC 121, equation (3) above has been used together with V(HB) to determine the distance modulus.

2.5 NGC 6553

As in the case of NGC 5927 (above), the metallicity of this cluster is greater than that of any cluster used to derive equation (2). Two distance moduli are given. One uses the data on the cluster from Ferraro et al. (1999) and equation (2) as described above. In the other case, the data are taken from Zoccali et al. (2001b) and equation (3) is used. Note the considerable difference in the reddening adopted in the two cases. The referee (Dr R. Gratton) has pointed out that a very recent paper (Carretta et al. 2001) gives [Fe/H] $= -0.06 \pm 0.15$ for this cluster and that Cohen et al. (1999) preferred $E(B-V) = 0.78$. With these values and V(HB) from Zoccali et al. (2001b) or V(ZAHB) from Ferraro et al. (1999), one obtains $M_K = -7.4$ or -7.6 for NGC 6553 V4. These figures become -7.2 or -7.4 if the lower luminosities for high metallicity RR Lyraes suggested by Caputo et al. (see Section 2.3) are used as a guide. These various values scatter round the value predicted by our final Mira PL(K) relation (-7.5).

2.6 NGC 5139 (ω Cen)

The distance modulus of this unusual cluster is quite uncertain at the present time. We adopt the value used by Hughes & Wallerstein (2000). These authors say that this distance (and reddening) are near the mean of several estimates and also give the best fit to isochrones. Because this distance is not derived in the same way as for the other clusters, we do not use ω Cen in our estimate of the Mira PL(K) zero-point. A distance modulus of 13.27 has recently been derived by van Leeuwen et al. (2000) from a comparison of radial velocities and proper motions in the cluster. However, the authors indicate that this distance should be regarded with considerable caution at the present time.

2.7 Terzan 5

The metallicity of this cluster is high, though rather uncertain. As in the case of the other very metal-rich clusters (NGC 5927 and 6553), the distance determination rests on an extrapolation of the Carretta et al. (2001) relations. In the case of V_S there are only observations at two well separated epochs. However, these differ in phase by about half a period so the mean of the two (which is given in Table 1) should be a fair approximation to the mean magnitude. The reddening is very high and varies across the cluster (Ortolani, Barbuy & Bica 1996). The $(J-K)$ colours of the two Miras in, or in the direction of, the cluster, together with the period–colour relation from Feast et al. (1989) show that their reddenings are similar [$E(J-K) = 1.10$ for variable V_S and 1.22 for variable V]. With a normal reddening law, these values lead to a mean $E(B-V)$ of 2.37, close to the value adopted by Ortolani et al. for the cluster. It is not known whether the Miras are radial velocity members of the cluster. Because the cluster is projected on the galactic bulge, it is quite possible that at least one of them is a field star. The relative magnitude of the two stars (compare their positions in Fig. 1) shows that if they both lie on the PL(K) relation, they do not have the same distance and therefore cannot both be cluster members.

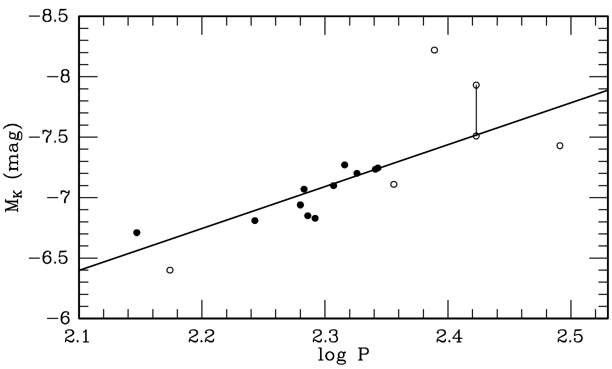

Figure 1. The M_K versus $\log P$ diagram for Miras in globular clusters. The objects with less certain distances are denoted by open circles. The two points joined by a vertical line are the two estimates for V4 in NGC 6553. The line is the LMC Mira relation with an LMC modulus of 18.59, from Cepheids.

3 DISCUSSION

Values of M_K are listed in Table 1 as derived from the data in that table and assuming $A_K = 0.273E(B-V)$. Fig. 1 shows the M_K–$\log P$ plot for these Miras. The line is the LMC Mira PL relation (equation 1) with $\gamma = 0.89$, where we have adopted a Cepheid distance modulus for the LMC of 18.59. This Cepheid modulus depends on LMC V,I photometry, a galactic zero-point calibration using parallaxes, proper motions and radial velocities, pulsation parallaxes and Cepheids in galactic clusters, together with a metallicity correction (Feast 2001a).[2]

It is evident in Fig. 1 that the agreement in the PL diagram of LMC field Miras with those in Galactic Globular Clusters and also the Mira in NGC 121 (SMC) is good. The most discrepant points are for the longer period Miras (V3 in NGC 5927, V4 in NGC 6553 and V and V_S in Terzan 5). In all these cases, as already noted, the estimate of the cluster distance involves an extrapolation and there are membership, reddening and other uncertainties in some of these cases. Thus the results for these clusters cannot be given any significant weight in the present discussion. As already indicated, the distance of ω Cen is also still quite uncertain and determined in a different way to that of the other clusters. The adopted distance gives a reasonable fit to the LMC Miras. If the shorter distance of van Leeuwen et al. (2001) were adopted, the Mira in the cluster would lie 0.7 mag below the LMC line. Thus if the variable is a normal Mira it provides some evidence against such a low distance.

Omitting the Miras from NGC 6553 and 5927, Terzan 5 and also the Mira in ω Cen, for the reasons just given, we are left with 11 Miras in seven clusters. Giving double weight to 47 Tuc and NGC 6356, which each have three Miras, and single weight to each of the other clusters, one finds a zero point for equation (1) of $\gamma = 0.93 \pm 0.14$. The estimated uncertainty comes from the uncertainties given by Carretta et al. (2000) for the coefficients of equations (2) and (3). The weighting adopted makes little

[2] The Cepheid metallicity correction for V,I photometry remains somewhat uncertain, though it seems unlikely to be significantly larger for the LMC than that used by Feast (2001a). It is of interest to note that the 'Cepheid galaxies' used by the *Hubble Space Telescope* Key project (Freedman et al. 2001) to calibrate their value of H_0 have a mean metallicity (weighted according to their contribution to H_0) very close to solar. Thus, using a galactic calibration, rather than a calibration based on an assumed LMC distance, would avoid the need to apply any significant metallicity correction (Feast 2001b).

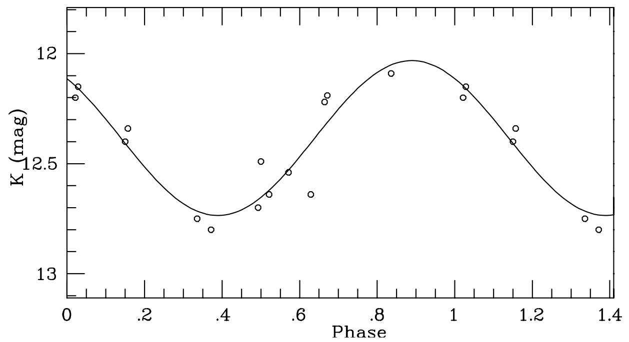

Figure 2. Light curve of NGC 121 V1. The curve shown is the best fitting sinusoid with a period of 139 d.

difference to the final result. If unit weight is given to each cluster, the value of γ only changes from 0.93 to 0.95.

The best value to adopt for the ratio, *R*, of total to selective absorption is somewhat uncertain. As already noted, we adopt the value of 3.1. Some authors (e.g. Ortolani et al. 2000) prefer to use a larger value (3.3). Using this larger value would have a significant effect on the results from clusters with high reddenings. In the case of the very heavily reddened cluster Terzan 5, the use of R = 3.3, would lead to values of M_K which are 0.5 mag fainter than the values given in Table 1 and plotted in Fig. 1. Fortunately the effect is small for the mean of the clusters used in determining γ. Adopting R = 3.3 would lead to $\gamma = 0.97$.

The result for V1 in the SMC globular cluster NGC 121 is particularly interesting. The star appears to be a normal Mira. Fig. 2 shows the *K* light curve of this star together with a Fourier fit. This gives a period of 139 ± 3 d in good agreement with Thackeray's (1958) determination of 140.2 d. The peak-to-peak pulsation amplitudes derived from Fourier fits ($\Delta J = 0.69$ mag; $\Delta H = 0.87$ mag; $\Delta K = 0.69$ mag) are within the range shown by globular cluster and solar neighbourhood Miras of similar period. The mean colours are $(J - H) = 0.72$ mag and $(H - K) = 0.20$ mag. These are bluer than predicted by the LMC period–colour relations (Glass et al. 1995) which give 0.83 and 0.25, respectively. However, this difference may not be significant. The variable has an M-type spectrum with Balmer line emission (Lloyd Evans 1983) as expected for an oxygen-rich Mira.

In a discussion of the Mira period–metallicity relation, Feast & Whitelock (2000) found that NGC 121 V1 fitted the relation well. In that discussion the globular cluster abundances used were primarily on the Zinn–West (Zinn & West 1984) scale, with [Fe/H] = −1.4 for NGC 121 being taken from Stryker, Da Costa & Mould (1985). Equation (7) of Carretta & Gratton (1997) shows that the abundance (−1.03) adopted above for NGC 121 from Dolphin et al. (2001), which is on the Carretta/Gratton scale, corresponds to −1.23 on the Zinn–West scale. Changing the metallicity of NGC 121 from −1.4 to −1.23 moves the point for V1 in the period–metallicity plot of Feast & Whitelock (2000) from just above to just below the mean line and does not affect the conclusion that this SMC cluster fits the mean relation well.

In the present paper we have preferred to use a globular cluster scale based on *Hipparcos* parallaxes of subdwarfs rather than rely on theoretical models. However, it is of interest to compare this scale with that derived by VandenBerg (2000) from theoretical ZAHB models. For the nine clusters used by Carretta et al. (2000, Table 3) to calibrate equations (2) and (3) (above), the mean difference between the true moduli derived from their work and those found from VandenBerg's models is only 0.06 ± 0.02, the VandenBerg scale being shorter. This is despite the fact that VandenBerg's (α-enhanced) model comparisons depend on a systematically different metallicity scale from that adopted by Carretta et al. This suggests that if the VandenBerg results were used for the clusters containing Miras (with metallicities placed on his adopted scale), our adopted zero-point which uses a mean of the cluster result with that obtained from *Hipparcos* parallaxes of field Miras (see Section 5) would only be made marginally larger.

4 AGB STARS AS EXTRAGALACTIC POPULATION INDICATORS

In an old or intermediate-age population the brightest individual stars will be on the thermally pulsing asymptotic giant branch (AGB) and the very brightest of these will be the Mira variables (Feast & Whitelock 1987; Whitelock & Feast 2000a). Because we lack any clear theoretical picture of evolution at the top of the AGB it has become common practice to compare extragalactic AGB stars with those in relatively well understood Galactic environments, e.g. globular clusters or the galactic bulge. Galactic Miras from specific environments have therefore become calibrators for whole populations in nearby galaxies wherever individual stars can be isolated and studied.

Fig. 3 shows the position of the globular cluster Miras from Table 1, i.e. of the tips of the cluster AGBs, in a colour–magnitude diagram which can be compared with extragalactic systems (after making any appropriate transformations to the colours). The Miras from Terzan 5 are omitted from this plot because their membership

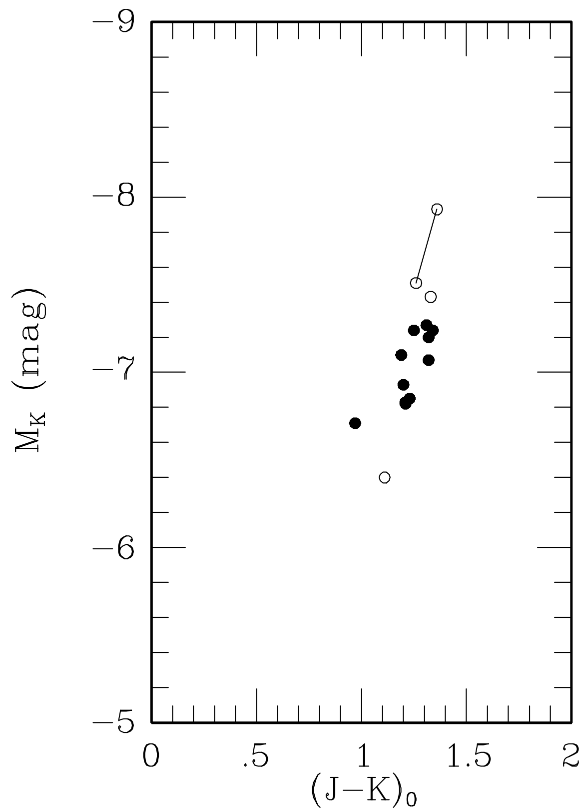

Figure 3. A colour–magnitude diagram for the Miras in Table 1, with symbols as in Fig. 1 (the Terzan 5 variables are omitted as discussed in the text).

is far from certain (see Section 2.7). Note that the spread in mean colour is small $\Delta(J-K) \sim 0.4$ for a range of $\Delta[Fe/H] > 0.5$. A comparison with Davidge's (2000) results suggests that the spread of age and metallicity in M32 may not be as small as he suggests.

It is sometimes considered instructive to compare extragalactic populations with the Galactic bulge and particularly with the M giants (mostly giant branch rather than AGB stars) in the NGC 6522 Baade Window (Frogel & Whitford 1987). This can be useful, but it is misleading to compare with the brightest stars in the Baade Window, because the line-of-site depth and large number of foreground stars in this Bulge field (Feast & Whitelock 1987; Tiede & Terndrup 1997) result in some spuriously luminous stars.

Guarnieri, Renzini & Ortolani (1997a) and Guarnieri et al. (1997b) compare the variable stars in NGC 6553, (see Section 2.5) of which the Mira V4 is the brightest, with AGB stars in M32. Using a distance modulus of 13.6 ± 0.25 they deduce that $M_K \sim -8.1$ for V4, which makes it almost as bright as the brightest AGB stars in M32 (note that all of the data they used, for NGC 6553 V4 and for M32 are from single epoch observations). The conclusion drawn is that the brightest stars in M32 need not be appreciably younger than those in the globular cluster. Davidge (2001) quotes Guarnieri et al. (1997a) as showing that V4 has $M_K = -8.5$. In fact V4 has an amplitude of $\Delta K \sim 0.5$ mag and even at maximum light at the larger distance quoted in Table 1 it will be no brighter than $M_K = -8.2$; if it is at the smaller distance it will be no brighter than $M_K = -7.8$. Furthermore, the discussion of Section 2.5 suggests that the lower of these two luminosities is more likely.

Thus whilst the luminosity of the AGB tip as defined by Mira variables may be a useful population indicator for old systems of known distance, it must be remembered that these stars are large amplitude variables. They are unlikely, therefore, to provide very specific calibrations from single epoch observations.

5 CONCLUSIONS

The zero-point of the Mira PL(K) relation (equation 1) as derived above from globular clusters (0.93 ± 0.14) agrees satisfactorily with that obtained from the *Hipparcos* parallaxes of local (field) Miras (0.84 ± 0.14) (Whitelock & Feast 2000b). A straight mean of these two independent estimates is 0.88 ± 0.10. This zero-point together with the data on LMC field Miras (Feast et al. 1989) then yields an LMC true modulus of 18.60, essentially the same as that derived from a metallicity corrected Cepheid *V,I* modulus ($18.59 \pm \sim 0.10$, Feast 2001a).

That the Mira in the SMC globular cluster NGC 121 fits both the Mira PL(K) and $P-$[Fe/H] relations well confirms the potential usefulness of these variables in deriving both distances and metallicities in old systems, including those beyond our own Galaxy. Even if periods are not known, Miras, as the brightest AGB stars, can be used to place some limits on stellar populations in old extragalactic systems provided mean infrared magnitudes and the distances of the systems are known.

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APPENDIX: NOTE ON PHOTOMETRIC SYSTEMS

All the observations used in this paper are on, or have been converted to, the natural system of the SAAO 1.9-m telescope, using the standard magnitudes from Carter (1990). This is the system adopted by Feast et al. (1989) for the data on the LMC Miras. Thus the data of Menzies & Whitelock (1985) has been adjusted by the zero-point corrections specified by Feast et al. (1989, appendix A). The data from Frogel et al. (1981) have been converted to the 1.9-m system using the transformations given by Carter (1990) and noting that $K_{1.9} = K_c$ and, for Miras, $(J - K)_{1.9} = 0.955(J - K)_c$ (Catchpole et al., unpublished; see Feast 1996). Here the subscript '1.9' refers to the 1.9-m natural system and the subscript 'c' to the 'standard' SAAO system, as defined by Carter (1990).

These conversions have no significant effect on the PL(K) results of this paper.

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