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AGB variables and the Mira period–luminosity relation

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ABSTRACT

Published data for large-amplitude asymptotic giant branch variables in the Large Magellanic Cloud (LMC) are re-analysed to establish the constants for an infrared (*K*) period–luminosity relation of the form $M_K = \rho[\log P - 2.38] + \delta$. A slope of $\rho = -3.51 \pm 0.20$ and a zero-point of $\delta = -7.15 \pm 0.06$ are found for oxygen-rich Miras (if a distance modulus of 18.39 ± 0.05 is used for the LMC). Assuming this slope is applicable to Galactic Miras we discuss the zero-point for these stars using the revised *Hipparcos* parallaxes together with published very long baseline interferometry (VLBI) parallaxes for OH masers and Miras in globular clusters. These result in a mean zero-point of $\delta = -7.25 \pm 0.07$ for O-rich Galactic Miras. The zero-point for Miras in the Galactic bulge is not significantly different from this value.

Carbon-rich stars are also discussed and provide results that are consistent with the above numbers, but with higher uncertainties. Within the uncertainties there is no evidence for a significant difference between the period–luminosity relation zero-points for systems with different metallicity.

Key words: stars: AGB and post-AGB – stars: carbon – stars: oscillations – stars: variables: other.

1 INTRODUCTION

Large-amplitude asymptotic giant branch (AGB) variables (Miras) are important distance indicators for old and intermediate age populations. They are luminous, both bolometrically and in the near-infrared (near-IR), and easily identified by their late spectral types (Me, Ce, Se or very rarely Ke), large amplitudes ($\Delta V > 2.5$ mag, $\Delta K > 0.4$ mag) and long periods ($100 \lesssim P \lesssim 1000$). The increasing use of adaptive optics on large telescopes at near-IR wavelengths to study stellar populations (e.g. Da Costa 2004) at large distances will require confidence in the calibration of the AGB variables as distance indicators. Alternatively, if the distance is known the luminosities of the brightest AGB stars provide insight into the intermediate age populations, e.g. Menzies et al. (2008).

Wood et al. (1999) demonstrated that, within the LMC, AGB variables fall on a series of, approximately parallel, period–luminosity (PL) relations at *K* (see also Cioni et al. 2001; Ita et al. 2004; Fraser et al. 2005; Soszyski et al. 2007). The large-amplitude variables, i.e. the Miras, however, lie only on a singe PL(*K*) relation. The existence of a Mira PL(*K*) relation has been known for some while (Feast et al. 1989; Hughes & Wood 1990) and is now generally thought to represent the relation for fundamental pulsation. While some of the low-amplitude variables also pulsate in the fundamental, others show various overtones. Low-amplitude variables are of limited use for distance scale studies as it is not simple to establish upon which of the various PL relations they lie. Complications do arise at periods in excess of about 400 d where some Miras in the LMC have higher luminosities, possibly as a consequence of hot bottom burning (HBB) (e.g. Whitelock et al. 2003). Feast (2004) provides a recent discussion of AGB stars as distance indicators and of the zero-point of the PL relation.

Following a brief re-examination of the Mira PL(*K*) relation in the LMC, we take advantage of the new analysis of the *Hipparcos* data (van Leeuwen 2007a,b, see also van Leeuwen 2005 and van Leeuwen & Fantino 2005) to re-examine the distance scale for large-amplitude AGB variables within the Galaxy. Analysis of the original *Hipparcos* data was discussed by van Leeuwen et al. (1997), Whitelock & Feast (2000, hereafter Paper I) and Knapp et al. (2003).

In the last part of this paper we put together all the available information on Mira parallaxes to establish the best value for the zero-point of the Mira PL(*K*) relation for the Galaxy and compare this with values for elsewhere.

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2 THE LMC PL(*K*) RELATION

Table 1 lists the data for the LMC stars, with periods less than 420 d, which we use here to establish the PL(*K*) relation. The starting point is the material from Feast et al. (1989) for large-amplitude variables with multiple observations. This is modified in light of Glass & Lloyd Evans (2003) who used MACHO data to refine the periods for the same group of stars and to eliminate three of them (W19, W30, W46) as semiregular (SR), rather than Mira, variables. To this is added the observations from Whitelock et al. (2003) for three new O-rich and four C-rich Miras within our period range, as well as additional material for two O-rich stars (R105, 0517−6551) already in the sample. The changes introduced by the two 2003 papers are minor and this data set is only marginally different from that used by Feast et al. (1989).

Twenty nine M-type Miras together with one S-type and one K-type Mira are analysed together as O-rich stars. An interstellar extinction correction of $A_K = 0.02$ mag (Feast et al. 1989) was applied to the data in Table 1. The PL(*K*) relation is fitted in the form

$$M_K = \rho[\log P - 2.38] + \delta, \qquad (1)$$

where M_K is the absolute *K* magnitude, *P* the pulsation period of the Mira and δ the zero-point of the PL(*K*) relation, which has a slope ρ. In previous work, by ourselves and others, zero-points have been derived at $\log P = 0$, far outside the range of Mira periods. The distance modulus of the LMC is taken to be $(m - M)_{\rm LMC} = 18.39 \pm 0.05$ (van Leeuwen et al. 2007).

Table 2 lists the values of the slope and zero-point found by least squares fitting separately to the O-rich stars and to the C-rich stars as well as to both groups together; σ is the standard deviation of the best fit. The results are illustrated in Fig. 1. There is no significant difference in the slope determined for the O- and C-rich Miras. If we use the slope found for the O-rich sample and apply it to the C-rich sample we find a zero-point of $\delta + (m - M)_{\rm LMC} = 11.148 \pm 0.032$. Thus the difference between the zero-points for the C- and O-rich Miras is 0.093 ± 0.041.

The slope determined above for the LMC O-rich Miras, i.e. $\rho = -3.51 \pm 0.20$ can be compared with the value of -3.59 ± 0.06 obtained by Ita et al. (2004) for LMC stars close to PL(*K*) sequence C and selected by colour to be O-rich. While the error shows this number is well defined, Ita et al. include some low amplitude, i.e. non-Mira, variables in the fit. Furthermore, it seems tautological to define the PL relation in terms of stars that were selected because they fell on sequence C. Rejkuba (2004) found a very similar slope, -3.37 ± 0.11, for colour selected Miras in Cen A, supporting the assumption that this PL(*K*) relation is universal.

3 THE REVISED *Hipparcos* SAMPLE AND ASSOCIATED DATA

Of the sample selected in Paper I there are astrometric data in the revised *Hipparcos* catalogue (van Leeuwen 2007a) for 184 O-rich Miras, 15 O-rich SRs and 40 C-rich variables.

In Paper I a number of non-Mira variables were included in the selection on the basis of their spectra, which were Mira-like in that they showed the emission lines that are characteristic of the shock waves associated with pulsations in Miras. For the O-rich stars four of the 15 SR variables included in the sample have large amplitudes (ΔHp > 1.5 mag, where *H*p is the broad-band visual magnitude measured by *Hipparcos*) and it is probably only these four, T Ari, T Cen, W Hya and TV And, that we should include with the Miras in

Table 1. LMC variables used to establish the slope for the Mira PL(*K*) relation.

Name	*P* (d)	*K* (mag)	Note
	O-rich stars		
0517−6551	116	12.25	
C38	130	12.12	
0512−6559	141	12.13	
W132	156	11.67	
0526−6754	157	11.79	
W151	174	11.74	
W148	183	11.82	
W158	194	11.77	
0528−6531	195	11.48	
C11	202	11.51	
GR13	202	11.59	
SHV05220−7012	205	11.73	1
0507−6639	208	11.57	
C20	210	11.54	
W77	213	11.25	S
R120	217	11.38	
W94	220	11.28	
W74	231	11.49	
WBP74	233	11.50	1
W1	235	11.48	
W140	243	11.19	
0533−6807	247	11.38	
R141	258	10.99	
R110	261	11.29	
W48	279	10.99	
0537−6607	284	11.02	
0505−6657	307	10.67	
0524−6543	315	10.71	
W126	318	10.89	K
SHV05305−7022	362	10.57	
R105	413	10.33	
	C-rich stars		
0530−6437	157	12.08	
0515−6617	226	11.16	
0528−6520	229	11.08	
0520−6528	233	11.28	
0519−6454	242	11.09	
W220	281	10.83	
0529−6759	283	10.91	
0515−6451	284	10.81	
SHV05027−6924	298	10.82	
0514−6605	308	10.64	
0534−6531	308	10.98	
0529−6739	319	10.60	
0502−6711	322	10.53	
C7	327	10.69	
0541−6631	342	10.50	
R153	347	10.52	
WBP14	351	10.62	
W103	363	10.78	
0515−6438	365	10.90	
0537−6740	367	10.47	
SHV05003−6817	369	10.58	
SHV05260−7011	373	10.54	

Notes: 1. Period taken from MACHO; S and K are spectral types.

Table 2. Solutions of equation (1).

Type	No.	σ	ρ	$\delta + (m - M)_{\rm LMC}$	δ
O-	31	0.14	-3.51 ± 0.20	11.241 ± 0.026	-7.15 ± 0.06
C-	22	0.15	-3.52 ± 0.36	11.149 ± 0.047	-7.24 ± 0.07
All	53	0.15	-3.69 ± 0.16	11.206 ± 0.020	-7.18 ± 0.05

the parallax analysis. For the C-rich stars it is actually very difficult to distinguish between Miras and non Miras (see also Whitelock et al. 2006).

The IR and associated data used in the following analysis are listed in Appendix A (Table A3), which also includes all details which differ from Paper I.

3.1 The SP-red and SP-blue stars

Whitelock, Marang & Feast (2000) divided the stars with periods below 225 d into two groups on the basis of their $H\text{p} - K$ colour, and called them the short period red (SP-red) and short period blue (SP-blue) groups. The analysis of Paper I suggested that the SP-reds were more luminous, at a given period, than the SP-blues. Most critically a kinematic analysis (Feast & Whitelock 2000) indicated that the SP-reds were younger than the SP-blues which were more akin to the globular cluster Miras and a natural extrapolation of the Miras with $P > 225$ d to shorter periods.

4 ANALYSIS OF *Hipparcos* DATA

We follow the same procedure as in Paper I and the details are not repeated here, but it is useful to give the formulae which differ slightly due to the reformulation of the PL(K) relation described in Section 2. We assume throughout that the slope derived above from the O-rich LMC Miras will be the same for the Galaxy. Thus equation (1) with, $\rho = -3.51 \pm 0.20$, is solved for δ, as previously, in the form

$$10^{0.2\delta} = 0.01\pi\, 10^{0.2(3.51[\log P - 2.38] + K_0)}, \tag{2}$$

where π is the parallax in milliarcseconds (mas) and K_0 is the mean K magnitude corrected for interstellar extinction (see Appendix A). The right-hand side of equation (2) is weighted by the following expression:

$$\text{weight} = 1/\left[\sigma\, 10^{0.2(K_0 + 3.51[\log P - 2.38]) - 2.0}\right]^2, \tag{3}$$

where

$$\sigma^2 = \sigma_\pi^2 + (0.4605)^2 \pi_{\mathrm{PL}(K)}^2 \left[\sigma_K^2 + \sigma_{\mathrm{PL}(K)}^2\right], \tag{4}$$

with σ_π the error on the parallax as quoted in the revised *Hipparcos* catalogue, $\pi_{\mathrm{PL}(K)}$ the photometric parallax derived from the PL(K) relation, $\sigma_{\mathrm{PL}(K)}$ the standard deviation from the PL(K) relation (0.14 and 0.15 for the O- and C-rich stars, respectively, see Table 2), and σ_K is the uncertainty associated with individual K_0 magnitudes. The latter term is evaluated as follows: $\sigma_K = 0.3\Delta K/\sqrt{N}$ (where N observations were used to derive the mean K_0). For further details refer to Paper I.

Due to uncertainties in the adopted slope, the error in a predicted absolute magnitude at any $\log P$ is, in the case of the O-Mira solution of Table 2:

$$\sqrt{\{[(\log P - 2.38)0.20]^2 + [0.06]^2\}}, \tag{5}$$

and similar relations apply in other cases.

R Leo has a parallax measured by the Allegheny Observatory at $\pi = 8.3 \pm 1.0$ mas (Gatewood 1992). For the analysis this is combined with the *Hipparcos* value, $\pi = 14.03 \pm 2.65$, to give $\pi = 9.01 \pm 1.42$.

4.1 Zero-point from the *Hipparcos* parallaxes

4.1.1 O-rich stars

The first part of Table 3 lists various values of δ, from equation (2) (weighted according to equations 3 and 4), derived from different subgroups of the *Hipparcos* data. In examining these results it is crucial to remember that most of the weight resides with a small number of stars.

Solution 1 shows the result of using all of the O-rich stars for completeness and comparison with Paper I, although it is quite clear that this is not a useful solution as there are stars included in the full group that are not large-amplitude variables and which certainly lie on one of the PL(K) relations above the one for Miras (see also Glass & van Leeuwen 2007). W Cyg is the most obvious example and solution 2 shows the effect of leaving it out. In fact solution 2 is very close to the best solution we obtain.

Solutions 3 and 4 are for large-amplitude variables and Mira variables, respectively; the results are very similar as might be expected.

Solutions 5–8 show the results of separating out the SP-red and SP-blue stars (see Section 3.1). In fact there is no evidence here for a significant difference between the groups, provided that W Cyg is omitted, with the revised *Hipparcos* data.

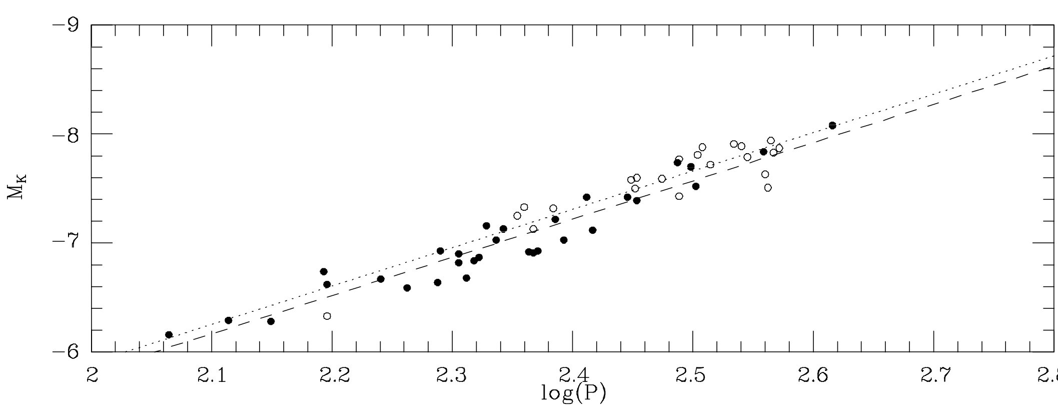

Figure 1. The PL(K) relation for Mira variables in the LMC. Solid and open symbols are O- and C-rich, respectively. The dashed line is the fit to the O-rich stars from Table 2 assuming a distance modulus for the LMC of 18.39 mag, while the dotted line is the relation for C-stars.

Table 3. PL(K) zero-point (δ) (preferred solutions to the analysis of the *Hipparcos* data are shown in bold face).

Solution no.	Number of stars	Weight ($\times 10^{-3}$)	δ (mag)	σ_δ	Stars included in the analysis
		Oxygen-rich stars from *Hipparcos*			
1	199	710	−7.46	0.11	All
2	198	572	−7.24	0.11	All but W Cyg
3	182	453	−7.27	0.13	ΔHp > 1.5 mag
4	184	385	−7.22	0.14	Mira variables
5	183	460	−7.28	0.13	All but SP-red stars
6	37		−7.59	0.46	SP-blue stars
7	16	259	−7.81	0.22	SP-red stars
8	15	112	−7.11	0.14	SP-red stars not W Cyg
9	**168**	**434**	**− 7.27**	**0.14**	Not SP-red stars; ΔHp > 1.5 mag
10	**42**	**415**	**− 7.32**	**0.10**	Miras; non-Miras with ΔHp > 1.5 mag; weight >1.3×10^3
11	146	433	−7.26	0.14	$P > 224$ d
12	21	84	−7.04	0.27	$P \geqslant 400$ Miras & non-Miras with ΔHp > 1.5 mag
13	6		−7.11	0.17	$\sigma_\pi/\pi < 0.16$, Miras, non-Miras with ΔHp > 1.5 mag
	Carbon-rich stars from *Hipparcos*				
14	40	97	−7.91	0.41	All
15	39	72	−7.55	0.40	Omitting WZ Cas
16	38	72	−7.55	0.40	Omitting WZ Cas and WX Cyg
	Carbon-rich stars omitting WZ Cas and WX Cyg				
17	23	24	−7.21	0.65	Miras only
18	31	33	−7.14	0.50	ΔHp > 1.0 mag
19	30	30	−7.03	0.50	ΔHp > 1.0 mag, omitting V Hya
20	24	46	−7.74	0.60	$P < 400$
21	14	26	−7.24	0.50	$P \geqslant 400$
22	35	70	−7.57	0.43	Hp − K < 8.5
23	15	48	−7.73	0.45	Non-Miras
24	16	32	−7.18	0.37	ΔHp > 1.0 mag, weight > 0.24×10^3
	Values derived in other ways				
25	5		−7.08	0.17	VLBI parallaxes for OH-Miras (Section 5.1.1, Table 5)
26	11		−7.34	0.13	Globular cluster Miras (Section 5.2)
27	31		−7.15	0.06	LMC O-rich Miras (Section 2)
28	22		−7.24	0.07	LMC C-rich Miras (Section 2)
29	54		−7.04	0.11	Miras in the Galactic bulge (Section 5.3)

Solution 9 omits the small amplitude variables and the SP-red stars and can be compared with $\beta = 0.84 \pm 0.14$ [$\delta \sim -7.51$ for a slightly different slope for the PL(K) relation], the solution of choice from Paper I. Solution 10 rejects the low-amplitude non-Miras and takes only the 42 stars with weight $>1.3 \times 10^3$. If we were to decide that the SP-reds should be included, despite their kinematic differences from the SP-blues, then this solution, with its marginally smaller error, might be preferred, but it makes very little practical difference.

Solutions 11 and 12 show that much the same value of δ is derived from the longer period stars alone. It is important to note there is thus no reason to suspect that they are brighter or fainter than their short period counterparts (see also Sections 5.1.1 and 5.1.2).

Solution 13 was derived in a different way and is discussed below (Section 4.1.3).

4.1.2 C-rich stars

Solutions 14–24 apply to subsets of the data for C-rich stars. We note again that it is difficult to distinguish between Mira and non-Mira C-stars and that the amplitudes of the C-rich stars are on average distinctly lower than those of their O-rich counterparts. As in Paper I we note that WZ Cas and WX Cyg are lithium-rich and therefore likely to differ from other stars in the sample. WZ Cas has a high weight and is clearly more luminous than the bulk of the sample. WX Cyg makes little difference, but we leave both stars out for most of the solutions (17–24).

The errors are high and it is difficult to deduce much about the subgroupings of C stars. The non-Miras may have a lower value of δ (solution 23) than the Miras (solution 17) or the large-amplitude variables (solution 18); this is to be expected if some of the low-amplitude variables lie on overtone sequences, but cannot be claimed with confidence. Solution 24 is probably the best, including only the higher weight stars with large amplitudes. V Hya is in a binary system (see Olivier, Whitelock & Marang (2001) and references therein), although its normal variations are due to pulsation. Solution 19 was derived leaving out V Hya.

These various solutions indicate that within the errors the C- and O-rich stars obey the same PL relation at K, which is consistent with earlier findings from the LMC (Section 2 and Feast et al. 1989).

4.1.3 Individual stars with low uncertainty

As an alternative approach, because there are a few stars with good signal-to-noise ratios, we selected stars with positive *Hipparcos*

Table 4. Data for individual stars with $\sigma_\pi/\pi < 0.16$.

Name	π	K_0	LK	Type	log P	M_K
o Cet	10.91 ± 1.22	−2.45	−0.10	M	2.521	$-7.37^{+.26}_{-.23}$
L_2 Pup	15.61 ± 0.99	−2.24	−0.03	SR	2.149	$-6.31^{+.14}_{-.13}$
R Car	6.34 ± 0.81	−1.35	−0.13	M	2.490	$-7.48^{+.30}_{-.26}$
R Leo	9.01 ± 1.42	−2.55	−0.20	M	2.491	$-7.98^{+.37}_{-.32}$
R Hya	8.24 ± 0.92	−2.47	−0.10	M	2.590	$-8.01^{+.26}_{-.23}$
W Hya	9.59 ± 1.12	−3.16	−0.11	SR	2.558	$-8.37^{+.27}_{-.24}$
W Cyg	5.72 ± 0.38	−1.40	−0.04	SR	2.117	$-7.65^{+.15}_{-.14}$
R Cas	7.95 ± 1.03	−1.79	−0.14	M	2.633	$-7.43^{+.30}_{-.26}$

parallaxes for which $\sigma_\pi/\pi < 0.16$ (Table 4). These are the same stars which dominate the various solutions discussed in Section 4.1.1, as the eight stars involved have 62 per cent of the weight of the complete sample of 199 O-rich stars. There are no C-stars with $\sigma_\pi/\pi < 0.16$. The eight include three non-Mira variables, W Cyg, L2 Pup and W Hya, of which only the latter is a large-amplitude variable. In view of the fact that these stars were selected on the basis of their σ_π/π ratio a Lutz–Kelker correction has been applied to their apparent magnitudes. This is evaluated (on the model used by Benedict et al. 2007) as

$$\mathrm{LK} = -8.09(\sigma_\pi/\pi)^2,$$

and it makes them up to 0.2 mag brighter than they would otherwise be. The corrections are listed in Table 4.

These stars are shown in the PL(K) diagram, Fig. 2, where they are compared with the stars discussed below. The PL(K) relation zero-point derived from the six stars W Hya, R Hya, R Cas, R Car, *o* Cet and R Leo, $\delta = -7.11 \pm 0.17$, is listed as solution 13 in Table 3. Note that the two low-amplitude SRs, W Cyg and L_2 Pup, which have $\sigma_\pi/\pi < 0.16$ and are shown in the figure are omitted from this solution for consistency.

5 OTHER MIRAS WITH ACCURATE DISTANCES

5.1 Miras with VLBI parallaxes

Parallaxes for the OH and H_2O masers associated with Miras promise to provide accurate distances for significant numbers of AGB stars. These techniques will be particularly important in establishing the distances to stars with high mass-loss rates, for which circumstellar extinction makes optical measurements extremely difficult.

5.1.1 Miras with OH parallaxes

Vlemmings et al. (2003) and Vlemmings & van Langevelde (2007) have published the results of astrometry for five stars, which are listed in Table 5 together with mean K magnitudes from SAAO photometry or the literature after correcting for interstellar extinctions determined as described in Appendix A. The *Hipparcos* and very long baseline interferometry (VLBI) parallaxes agree within the quoted uncertainties.

The parallaxes of these five OH masers, alone, give a zero-point for the PL(K) relation of $\delta = -7.08 \pm 0.17$. As Vlemmings & van Langevelde (2007) pointed out, the results for U Her seem to be different from the others, but taken with the *Hipparcos* results the difference is not obviously significant.

van Langevelde, van der Heiden & van Schooneveld (1990) measured phase-lag distances to more than 12 OH/IR sources (essentially Miras with high mass-loss rates and therefore thick dust shells). The K magnitudes of these stars experience significant circumstellar extinction and they cannot therefore easily be presented in a PL(K) relation. Their position in a PL(M_{bol}) relation was discussed by Whitelock, Feast & Catchpole (1991, their fig. 10) from which they appear to be consistent with the PL(M_{bol}) relation extrapolated from shorter periods. Phase-lag distances might still prove useful for the longest period objects although it will be difficult to bring the errors down so that they can compete with VLBI parallaxes.

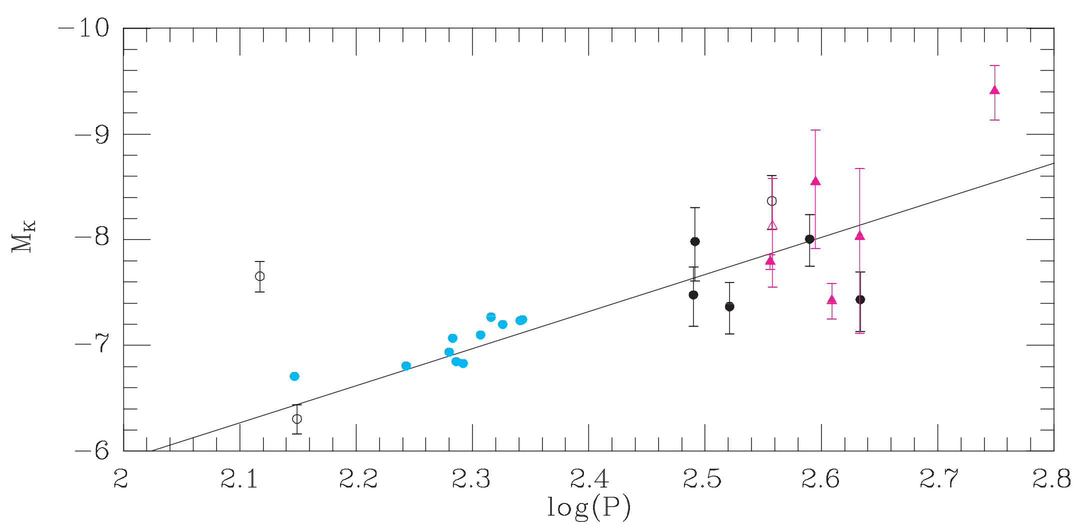

Figure 2. The PL(K) relation for AGB variables with good individual distances. The closed and open symbols represent Miras and SR variables, respectively; the points without error bars are for the globular cluster Miras, the circles with error bars represent the *Hipparcos* data with high S/N (Table 4) and the triangles represent VLBI parallaxes (Table 5). The line is for $M_K = -3.51\,[\log P - 2.38] - 7.25$.

Table 5. Data for stars with VLBI parallaxes.

Name	$\pi_{\rm VLBI}$	$\pi_{Hipparcos}$	K_0	Type	log P	M_K	Reference
S CrB	2.39 ± 0.17	1.85 ± 1.19	0.32	M	2.556	$-7.79^{+.07}_{-.07}$	V07
U Her	3.76 ± 0.27	4.06 ± 1.19	−0.30	M	2.609	$-7.42^{+.17}_{-.17}$	V07
RR Aql	1.58 ± 0.40	–	0.46	M	2.595	$-8.55^{+.63}_{-.49}$	V07
W Hya	10.18 ± 2.36	9.59 ± 1.12	−3.17	SR	2.558	$-8.13^{+.57}_{-.45}$	V03
R Cas	5.67 ± 1.95	7.95 ± 1.03	−1.80	M	2.663	$-8.03^{+.92}_{-.64}$	V03
UX Cyg	0.54 ± 0.06	–	1.93	M	2.749	$-9.41^{+.27}_{-.24}$	K05

References: V07 – Vlemmings & van Langevelde (2007); V03 – Vlemmings et al. (2003); K05 – Kurayama et al. (2005).

5.1.2 *Mira with H_2O parallax*

Kurayama, Sasao & Kobayashi (2005) published an accurate H_2O maser parallax for UX Cyg which is given in Table 5 and illustrated in Fig. 2. It lies distinctly above the Mira PL(K) relation. This may indicate that it is an overtone pulsator and that it therefore lies on one of the other PL relations discussed by Wood (2000), although it has a longer period than any of the LMC stars on those sequences. The stars that define the other PL(K) relations are low-amplitude SR variables, and it would be surprising to find a star like UX Cyg in this position. However, the PL(K) sequences were defined for stars in the Magellanic Clouds, all of which are at the same distance, and very little is actually know about the distances of stars with periods significantly longer than 400 d in the Galaxy (except close the Galactic Centre, where interstellar extinction is very high and patchy). Note that solution 12 (Table 3) for the 21 *Hipparcos* stars with $P \geqslant 400$ d gives a zero-point completely consistent with them lying on the same PL(K) relation as the shorter period objects.

The alternative explanation is that UX Cyg is more luminous than those on the PL(K) relation as a result of HBB, and is therefore akin to the luminous Magellanic Cloud Miras discussed by Whitelock et al. (2003). This could be confirmed by the detection of abundance anomalies associated with HBB, which include a measurable lithium content. Note that the long period O-rich LMC Miras that Whitelock et al. (2003) thought lay close to the extrapolated *bolometric* PL relation, would actually lie below a PL(K) relation because the significant circumstellar reddening would effect their apparent K luminosities.

UX Cyg is not included in evaluating the mean PL(K) relation zero-point below.

5.2 Globular clusters

Feast, Whitelock & Menzies (2002) discussed the PL relation for globular cluster Miras, using a distance scale based on *Hipparcos* parallaxes for subdwarfs (from Carretta et al. (2000) who estimate the total uncertainty at ±0.12 mag). Re-analysing those data using equation (1) with $\rho = -3.51 \pm 0.20$ we find a PL(K) relation zero-point of $\delta = -7.34 \pm 0.04$ (internal error), or $\delta = -7.34 \pm 0.13$ allowing for the uncertainty in the cluster scale. The points for the individual Miras are illustrated in Fig. 2.

5.3 The Galactic bulge

Glass et al. (1995) discussed long period variables in the Sgr I window of the Galactic bulge and derived a similar slope for the PL(K) relation to the one found here (Section 2) for the LMC. Re-analysing these, as above, gives $\delta + (m - M)_{\rm GC} = 7.40 \pm 0.05$. Using the Eisenhauer et al. (2005) distance to the centre, with the relativistic correction suggested by Zucker et al. (2006), gives $(m - M)_{\rm GC} = 14.44 \pm 0.09$, and provides a zero-point of $\delta = -7.04 \pm 0.11$ for these Galactic bulge Miras. The similarity of this to the other values found here suggests that any abundance effects on the PL(K) relation zero-point must be small.

In the conclusion below we do not average this bulge distance along with the other values to get a mean zero-point for the Galaxy. If we did so the agreement of the Galactic mean with the LMC would be even closer. However, there are systematic uncertainties associated with the bulge (including its shape and structure) that suggest it should not be treated in the same way.

6 CONCLUSIONS

In Paper I (Section 2.2) we noted a caveat with regard to temporal changes in the light distribution across the stellar disc as problematic for the interpretation of the parallaxes. This is particularly so because the angular diameters of the Miras are two or three times larger than their parallaxes. More recent work (e.g. Ragland et al. 2006; Woodruff et al. 2008) confirms that the diameters are large, variable and non-uniform. These same references further highlight the disagreement between observation and theory, emphasizing our very limited understanding of the atmospheres of these stars or their variations. This is clearly a real problem, but the agreement on the distance scale achieved by the different methods summarized above may indicate that the net effect is small.

As noted, the various results discussed above are in good agreement with each other. UX Cyg is brighter than we would expect from the PL(K) relation and this may be because of HBB. We take a simple mean of solutions 10, 25, 26 from Table 3 to set a mean value of $\delta = -7.25 \pm 0.07$ for the O-rich Mira variables in the Galaxy. This is in reasonable agreement with the LMC value of $\delta = -7.15 \pm 0.06$.

Solution 24, for the C-rich Miras, of $\delta = -7.18 \pm 0.37$ is in agreement with the above result for O-rich Miras and with the LMC value for C-stars of $\delta = -7.24 \pm 0.07$. This supports an identical PL(K) relation for O- and C-rich variables.

The O-rich result represents the best value for large-amplitude variables, but it should be used with caution on stars with periods in excess of 400 d. The H_2O parallaxes offer the most likely significant improvement in this result in the near future.

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APPENDIX A: INFRARED PHOTOMETRY AND BASIC DATA

The IR K magnitudes used here are largely those used in Paper I, with updates where significant quantities of new data are available. New IR photometry has been obtained from SAAO for 10 stars: W Psc, WW Vel, RT Crt, S CrB, S Ser, BG Ser, R Ser, RU Her, T Her and W Sex. This is listed in Table A1 (the full table is available online) together with previously published data for the same stars. Six of these stars have sufficient data to derive periods (more than nine observations) and their light curves are illustrated in Fig. A1. A description of the photometer, telescope, etc. was given in Whitelock et al. (2000).

Table A1. New IR photometry from SAAO (the full table is available online; see the Supplementary Material section).

JD −244 0000 (d)	J	H (mag)	K	L
W Psc Hip 4652				
9356.26	6.91	6.01	5.69	5.34
10053.29	6.96	6.02	5.69	5.24
10295.64	6.92	6.01	5.65	5.26
10320.57	7.22	6.33	5.93	5.44
10360.46	7.44	6.57	6.14	5.80
10414.31	7.28	6.41	6.08	5.52
10721.47	7.34	6.47	6.05	5.69
10796.28	7.13	6.21	5.89	5.38
11068.27	7.13	6.22	5.83	5.41
11104.27	7.47	6.58	6.16	5.72
12977.29	7.55	6.66	6.24	5.77

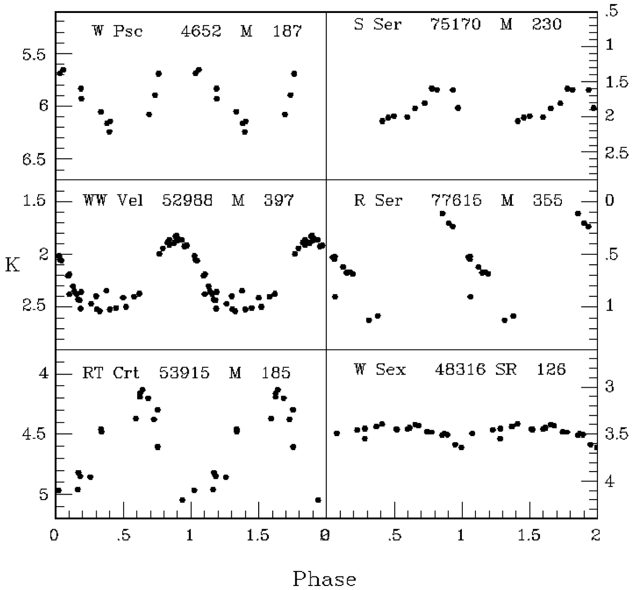

Figure A1. Light curves for Mira variables with new photometry and observations on at least 10 epochs. These are plotted at arbitrary phase and each point is shown twice to emphasize the periodicity. The name, *Hipparcos* number, type of variability (M or SR) and period at which the data are phased, is given on each plot.

A1 Interstellar extinction

The interstellar extinction corrections used here are derived in a different way from those used in Paper I. A first estimate is made of the distance to the Mira assuming no interstellar extinction and equation (1) of Section 2 with $\rho = -3.51 \pm 0.20$ and $\delta = -7.25$. The extinction is then estimated using the Drimmel, Cabrera-Levers & López-Corredoira (2003) three dimensional Galactic extinction model, including the rescaling factors that correct the dust column density to account for small-scale structure seen in the DIRBE data, but not described explicitly by the model. The measured mean *K* magnitude is then corrected for extinction following the reddening law given by Glass (1999) and the procedure iterated; two iterations usually suffice.

This procedure gives significantly different, in many cases larger, extinctions for individual stars from the statistical method applied by Whitelock et al. (2000) and used in Paper I. The biggest difference among the O-rich stars is for UX Oph which has $A_V \sim 1.51$ mag according to the method used here, in contrast to the $A_V \sim 0.23$ mag used in Paper I. Nevertheless, the net effect on the derived zero-point is negligible, first because the reddening at *K* is low, and secondly, because the stars with the highest weight are the closest and have the least reddening.

A2 Pulsation periods and amplitudes

Pulsation periods, P_K, and peak-to-peak amplitudes, ΔK, were derived for the stars with nine or more SAAO observations. These are listed in Table A2 along with Fourier mean magnitudes, *JHKL*, for all of the stars with new observations (see also Fig. A1).

In general we use the pulsation periods tabulated in the General Catalogue of Variable Stars (GCVS, Kholopov et al. 1985) for the parallax analysis, as these are usually based on large data sets. However, Whitelock et al. (2000) noted the very significant difference between the GCVS and *Hipparcos* periods for RT Crt, WW Vel and W Sex (their fig. 1). We now have sufficient IR data to be confident

Table A2. Fourier mean photometry and other data for stars with new SAAO *JHKL* observations.

Hip no.	Name	J	H	K (mag)	L	ΔK	No.	P (d)	P_K	Type
4652	W Psc	7.18	6.28	5.92	5.47	0.62	11	188	187	M
48316	W Sex	5.09	3.94	3.48	3.05	0.11	21	200	126	SR
52988	WW Vel	3.72	2.70	2.23	1.71	0.69	38	392	397	M
53915	RT Crt	5.88	5.04	4.58	3.96	0.88	16	183	185	M
75143	S CrB	1.69	0.74	0.22	−0.32	0.64	8	360	–	M
75170	S Ser	3.45	2.42	1.88	1.31	0.41	10	372	230	M
77027	BG Ser	1.95	0.85	0.39	−0.04	0.31	8	404	–	M
77615	R Ser	2.03	1.11	0.63	0.03	0.70	13	356	355	M
79233	RU Her	1.96	0.88	0.34	−0.25	0.73	9	485	482	M
88923	T Her	4.46	3.67	3.35	2.91	0.42	4	165	–	M

that the *Hipparcos* periods are correct for RT Crt and WW Vel. W Sex is a low-amplitude variable C-star and its period is not well determined from the IR observations although the *Hipparcos* value of 200 d seems better than the 134 d GCVS value. We therefore use the *Hipparcos* values for all three stars in the parallax analysis, in preference to the GCVS values (see also Fig. A1).

Note that although the period derived from the IR data, P_K, for S Ser, 230 d, is significantly different from the 372 d given in the GCVS (*Hipparcos* derived 376), we use the GCVS value in the analysis as there are insufficient IR data to be confident in any period derived from them. Note also that although BG Ser is classified as a Mira, its amplitude, $\Delta K = 0.31$ is low and more typical of an SR variable. The values used in the analysis are listed in Table A3.

A3 The data

Table A3 contains the material used in, and derived from, the analysis related to the IR magnitudes. The columns are as follows:

(1) the GCVS variable star name;
(2) the *Hipparcos* catalogue number;
(3) the variability type: mostly Mira (M) or SR variables, with two slow irregulars (L or LB) among the C-stars;
(4) *P*, the period used in the analysis, which is generally that tabulated in the GCVS (see Section 6.2 for RT Crt, WW Vel and W Sex);
(5) ΔHp, the peak-to-peak amplitude of the variations in the *Hipparcos* magnitude; stars with large amplitudes, i.e. $\Delta H\text{p} > 1.5$ mag (O-rich) or $\Delta H\text{p} > 1.0$ mag (C-rich), are considered to be very similar to the Miras for most purposes;
(6) *K*, the mean *K* magnitude, before correcting for interstellar extinction;
(7) the number of observations used to derive the mean *K* in column (6) – where there are nine or more observations the value will probably be close to the true mean (see below for more details of the non-SAAO photometry);
(8) A_V, the interstellar extinction at *V* (see above), but note that this depends on the distance and the reddening should be regarded as a lower limit if it is uncertain that the star lies on the Mira PL(*K*) relation, i.e. if there is no entry in the 'dist' column (because almost all of the non-Mira variables lie on PL(*K*) relations above the Mira one);
(9) dist, the distance in kpc derived from equation (1), with $\rho = -3.51 \pm 0.20$ and $\delta = -7.25$ (the identical relation was used for O- and C-rich stars), dist is not given for stars which do not, or may not, lie on the Mira PL(*K*) relation, i.e. low-amplitude variables.

Table A3. IR and other data for variable stars.

Name	Hip no.	Type	*P* (d)	Δ*H*p (mag)	*K* (mag)	no.	A_V (mag)	dist (kpc)
Data for O-rich variables								
Z Peg	8	M	335	4.01	1.09	7	0.11	0.59
SV And	344	M	316	3.96	2.45	4	0.26	1.05
SW Scl	516	SR	146	1.30	3.72	4	0.04	
RU Oct	703	M	373	2.23	2.68	14	0.26	1.30
SS Cas	781	M	141	3.00	3.48	2	0.41	0.95
S Scl	1236	M	362	4.50	0.31	122	0.04	0.43
T Cas	1834	M	445	2.16	−1.04	8	0.15	0.27
R And	1901	M	409	4.27	0.01	7	0.17	0.41
T Scl	2286	M	202	2.88	3.74	9	0.06	1.39
TU And	2546	M	317	3.52	2.11	5	0.11	0.90
W Psc	4652	M	188	2.61	5.92	11	0.17	3.60
U Per	9306	M	320	2.36	0.89	5	0.27	0.51
Y Eri	9767	M	303	2.10	1.79	14	0.07	0.75
R Ari	10576	M	187	3.61	3.94	12	0.20	1.44
W And	10687	M	396	5.10	0.43	5	0.11	0.49
o Cet	10826	M	332	4.39	−2.45	104	0.04	0.11
R Cet	11350	M	166	4.25	2.54	30	0.10	0.70
S Tri	11423	M	242	1.46	3.86	3	0.21	1.66
U Cet	11910	M	235	3.88	2.77	25	0.06	0.99
R Tri	12193	M	267	3.96	0.97	13	0.13	0.47
T Ari	13092	SR	317	1.66	0.17	23	0.23	0.37
R Hor	13502	M	408	4.48	−0.93	52	0.07	0.27
T Hor	14042	M	218	3.29	3.32	14	0.06	1.21
X Cet	15465	M	177	2.68	4.23	15	0.16	1.59
RT Eri	16647	M	371	2.60	0.39	5	0.28	0.45
T Eri	18336	M	252	3.73	2.42	23	0.09	0.89
W Eri	19567	M	377	4.04	1.51	16	0.16	0.77
RS Eri	20045	M	296	3.05	1.22	5	0.12	0.57
R Ret	21252	M	278	3.42	1.74	22	0.09	0.69
RX Tau	21600	M	332	2.12	1.21	10	0.39	0.61
R Cae	21766	M	391	3.56	0.59	116	0.05	0.52
X Cam	22127	M	144	3.69	3.64	1	0.28	1.04
SU Dor	22256	M	236	3.44	5.09	11	0.03	2.90
T Lep	23636	M	368	2.89	0.09	16	0.06	0.39
U Dor	24055	M	394	3.38	1.17	35	0.11	0.68
S Pic	24126	M	428	4.37	0.72	93	0.05	0.59
T Pic	24468	M	201	4.04	4.26	14	0.07	1.77
R Aur	24645	M	458	3.72	−0.69	4	0.16	0.32
T Col	24824	M	226	2.79	1.96	14	0.06	0.66
R Oct	25412	M	405	4.00	0.75	6	0.38	0.57
S Ori	25673	M	414	3.05	−0.07	101	0.73	0.39
S Col	27286	M	326	3.22	1.59	12	0.07	0.73
U Ori	28041	M	368	4.90	−0.75	56	0.14	0.27
RS Aur	28714	SR	171	0.73	3.10	2	0.33	
X Aur	29441	M	164	2.86	3.43	3	0.32	1.03
V Mon	30326	M	340	4.20	1.08	20	0.29	0.59
RV Pup	32115	M	188	2.96	3.62	17	0.30	1.25
X Gem	32512	M	264	3.10	1.86	7	0.05	0.71
X Mon	33441	SR	156	1.17	2.87	20	0.39	
R Lyn	33824	M	379	4.29	2.14	4	0.14	1.04
R Gem	34356	M	370	4.31	1.67	4	0.04	0.82
L2 Pup	34922	SR	141	0.71	−2.24	71	0.04	
V Gem	35812	M	275	3.31	2.81	9	0.14	1.12
TT Mon	36043	M	323	3.86	1.95	7	0.38	0.84
VX Aur	36314	M	322	3.07	1.53	3	0.14	0.70
RX Mon	36394	M	346	3.72	2.67	6	0.11	1.24
S Vol	36423	M	395	3.67	2.41	3	0.59	1.18
Z Pup	36669	M	509	3.89	1.33	72	0.44	0.87
S CMi	36675	M	333	3.85	0.48	11	0.05	0.44
U CMi	37459	M	413	3.41	2.61	9	0.32	1.36
W Pup	37893	M	120	3.28	3.54	20	0.44	0.87
SU Pup	38772	M	340	5.45	2.58	11	0.34	1.16
AS Pup	39967	M	325	2.59	0.27	6	0.69	0.38
R Cnc	40534	M	362	3.32	−0.62	19	0.07	0.28
SV Pup	40593	M	167	3.78	3.59	4	0.24	1.13
S Hya	43653	M	257	4.08	2.85	11	0.16	1.09
T Hya	43835	M	299	3.98	2.36	14	0.09	0.97
W Cnc	44995	M	393	3.90	1.04	5	0.10	0.64
R Car	46806	M	309	4.27	−1.35	74	0.10	0.18
X Hya	47066	M	301	3.73	0.65	13	0.18	0.44
R LMi	47886	M	372	3.58	−0.34	10	0.04	0.33
R Leo	48036	M	310	3.46	−2.55	53	0.03	0.10
S LMi	48520	M	234	4.37	3.81	3	0.04	1.60
V Leo	49026	M	273	3.90	3.17	6	0.06	1.32
X Ant	49524	M	162	3.41	5.41	6	0.20	2.56
S Car	49751	M	149	2.79	1.87	34	0.18	0.47
W Vel	50230	M	395	3.62	0.56	13	0.42	0.51
V Ant	50697	M	303	3.97	2.10	9	0.30	0.86
S Sex	51791	M	265	2.72	3.42	12	0.21	1.44
R UMa	52546	M	302	4.18	1.37	13	0.07	0.62
WX Vel	52887	M	412	3.72	1.81	8	0.66	0.92
WW Vel	52988	M	392	2.77	2.23	38	0.58	1.08
CI Vel	53853	M	143	2.38	6.38	7	0.89	3.58
RT Crt	53915	M	183	3.20	4.58	16	0.12	1.91
DN Hya	57009	M	182	3.20	5.37	5	0.24	2.73
X Cen	57642	M	315	3.60	1.10	14	0.32	0.56
W Cen	58107	M	202	3.45	1.95	17	0.44	0.60
R Com	58854	M	363	4.35	2.21	8	0.06	1.04
R Crv	60106	M	317	4.10	1.88	19	0.17	0.81
XZ Cen	60502	M	291	1.95	1.51	4	0.23	0.64
T CVn	61009	M	290	1.41	2.04	6	0.04	0.82
U Cen	61286	M	220	3.53	3.13	8	0.61	1.09
T UMa	61532	M	257	4.13	2.74	6	0.03	1.04
R Vir	61667	M	146	3.27	2.05	10	0.06	0.51
S UMa	62126	M	226	3.00	3.04	3	0.04	1.09
U Vir	62712	M	207	3.80	4.01	7	0.07	1.61
BZ Vir	63501	M	151	2.15	5.35	4	0.24	2.37
V CVn	65006	SR	192	1.13	1.12	6	0.10	
R Hya	65835	M	389	2.71	−2.47	53	0.12	0.13
S Vir	66100	M	375	4.25	0.33	13	0.10	0.45
T Cen	66825	SR	90	1.79	2.50	27	0.12	0.45
RT Cen	67359	M	255	1.40	2.69	18	0.23	1.01
R CVn	67410	M	329	3.36	0.45	5	0.03	0.43
W Hya	67419	SR	361	2.02	−3.16	24	0.05	0.09
RX Cen	67626	M	328	4.99	2.77	16	0.25	1.24
RU Hya	69346	M	332	3.81	1.57	15	0.16	0.72
R Cen	69754	M	546	2.63	−0.70	66	0.21	0.36
U UMi	69816	M	331	2.51	0.71	2	0.06	0.49
S Boo	70291	M	271	3.89	3.11	2	0.02	1.28
RW Lup	70590	M	331	1.07	2.52	9	0.44	1.11
RS Vir	70669	M	354	3.71	1.10	30	0.09	0.61
R Boo	71490	M	223	3.82	2.11	6	0.06	0.71
RR Boo	72300	M	195	3.70	5.19	2	0.02	2.66
Y Lib	74350	M	276	4.17	3.29	15	0.24	1.40
RT Boo	74802	M	274	2.04	2.56	3	0.06	1.00
S CrB	75143	M	360	4.09	0.32	22	0.05	0.43
S Lib	75144	M	193	2.32	4.51	14	0.48	1.90
S Ser	75170	M	372	2.69	1.88	10	0.13	0.91
RS Lib	75393	M	218	2.58	−0.07	35	0.26	0.25
S UMi	75847	M	331	2.61	3.04	3	0.08	1.43
R Nor	76377	M	508	4.53	1.27	55	0.59	0.84
BG Ser	77027	M	404	2.04	0.39	8	0.36	0.48
T Nor	77058	M	241	3.93	2.16	6	0.49	0.75
X CrB	77460	M	241	3.59	3.42	2	0.06	1.36
R Ser	77615	M	356	4.54	0.63	13	0.12	0.49

Table A3 – *continued*

Name	Hip no.	Type	P (d)	ΔHp (mag)	K	no.	A_V (mag)	dist (kpc)
RZ Sco	78746	M	157	1.93	4.19	15	0.60	1.41
Z Sco	78872	M	343	1.78	1.48	15	0.82	0.69
RU Her	79233	M	485	4.46	0.36	20	0.19	0.54
U Her	80488	M	406	3.88	−0.29	20	0.14	0.36
R Dra	81014	M	246	3.85	2.26	4	0.08	0.81
SS Her	81026	M	107	2.68	5.08	8	0.24	1.64
AS Her	81506	M	269	3.44	1.94	5	0.16	0.74
S Her	82516	M	307	4.39	1.30	5	0.20	0.60
Z Ara	82695	M	289	3.46	3.20	4	0.59	1.37
RS Sco	82833	M	320	4.45	0.40	13	0.25	0.41
RR Sco	82912	M	281	3.34	−0.23	54	0.22	0.28
SY Her	83304	M	117	3.04	4.33	7	0.16	1.24
UX Oph	83582	M	117	3.15	4.71	3	1.51	1.40
Z Oph	84763	M	349	3.80	4.01	5	0.57	2.27
RS Her	84948	M	220	3.25	2.92	4	0.16	1.01
Z Oct	86836	M	335	2.48	2.72	2	0.45	1.22
T Her	88923	M	165	3.74	3.36	8	0.19	1.01
R Pav	89258	M	229	3.65	2.90	12	0.25	1.02
W Lyr	89419	M	198	3.37	3.22	5	0.10	1.08
RY Oph	89568	M	150	3.00	2.96	8	0.51	0.77
AL Dra	90474	M	330	3.20	2.99	4	0.23	1.38
RV Sgr	90493	M	316	4.44	1.62	18	0.35	0.71
RS Dra	91316	SR	283	0.61	1.96	3	0.27	
R Aql	93820	M	284	3.11	−0.76	45	0.13	0.22
SS Lyr	94438	M	346	2.80	1.94	3	0.17	0.88
RW Sgr	94489	SR	187	0.61	3.06	9	0.32	
R Sgr	94738	M	270	4.28	2.06	13	0.28	0.78
DD Cyg	96031	M	148	2.90	6.29	1	0.61	3.55
RT Aql	96580	M	327	3.22	1.12	9	0.27	0.58
BG Cyg	96647	M	288	1.19	1.06	3	0.24	0.52
RT Cyg	97068	M	190	3.68	3.23	3	0.19	1.05
chi Cyg	97629	M	408	5.51	−1.91	11	0.10	0.17
T Pav	97644	M	244	4.31	2.87	9	0.31	1.06
RR Sgr	98077	M	336	4.56	0.69	14	0.28	0.49
RU Sgr	98334	M	240	3.93	2.18	5	0.24	0.76
BQ Pav	98447	M	110	3.01	6.58	16	0.17	3.35
R Del	99802	M	285	3.20	1.93	5	0.41	0.76
RT Sgr	100033	M	306	3.99	1.33	7	0.14	0.61
CN Cyg	100048	M	199	2.99	4.05	1	0.61	1.56
V865 Aql	100599	M	367	3.20	1.60	7	0.42	0.78
U Mic	101063	M	334	3.55	1.84	21	0.15	0.83
R Mic	101985	M	139	3.58	3.66	7	0.18	1.03
S Del	102246	M	278	2.18	2.08	4	0.22	0.81
V Aqr	102546	SR	244	1.13	0.58	3	0.23	
AM Cyg	102732	M	371	2.42	1.88	2	0.44	0.89
T Aqr	102829	M	202	3.17	3.24	14	0.19	1.10
RX Vul	103069	M	457	1.54	1.06	2	0.34	0.71
R Vul	104015	M	164	3.60	3.24	2	0.44	0.94
V Cap	104285	M	276	3.51	3.48	11	0.15	1.53
T Cep	104451	M	388	3.45	−1.76	6	0.33	0.17
T Cap	105498	M	269	3.20	3.24	18	0.22	1.35
W Cyg	106642	SR	131	0.62	−1.40	4	0.06	
RU Cyg	107036	SR	233	0.75	−0.29	3	0.14	
TU Peg	107390	M	321	2.97	1.10	4	0.30	0.57
RS Peg	109610	M	415	3.14	1.20	7	0.17	0.71
DH Lac	109619	M	289	2.83	4.56	1	0.43	2.58
X Aqr	110146	M	312	3.65	2.96	18	0.10	1.32
UU Tuc	110451	M	335	3.08	3.53	66	0.08	1.80
RT Aqr	110509	M	246	1.46	2.17	20	0.08	0.78
T Gru	110697	M	136	2.35	5.24	14	0.04	2.10
S Gru	110736	M	402	4.38	0.68	14	0.03	0.55
S Lac	110972	M	242	3.40	2.42	4	0.47	0.85
SS Peg	111385	M	425	3.94	1.15	6	0.12	0.71

Table A3 – *continued*

Name	Hip no.	Type	P (d)	ΔHp (mag)	K	no.	A_V (mag)	dist (kpc)
T Tuc	111946	M	250	3.84	3.22	7	0.06	1.28
SX Peg	112784	M	304	3.53	3.15	7	0.22	1.41
TV And	113405	SR	114	1.71	3.50	1	0.53	0.82
RT Oct	113652	M	180	4.22	5.72	3	0.43	3.16
R Peg	114114	M	378	4.11	0.52	10	0.20	0.49
V Cas	114515	M	229	3.17	0.86	4	0.22	0.40
TY And	114757	SR	260	0.79	1.62	4	0.25	
W Peg	115188	M	346	2.58	−0.02	6	0.19	0.36
S Peg	115242	M	319	3.48	1.42	12	0.16	0.66
R Aqr	117054	M	387	3.82	−1.02	104	0.06	0.25
R Cas	118188	M	430	4.24	−1.79	13	0.10	0.19
Data for C-rich variables								
WZ Cas	99	SR	186	0.44	0.61	8	0.17	
W Cas	4284	M	399	2.02	2.77	14	0.64	1.44
R Scl	6759	SR	375	1.13	−0.09	157	0.07	0.37
\ X Cas	9057	M	420	1.44	2.37	4	0.59	1.24
R For	11582	M	385	3.30	1.21	100	0.04	0.68
Y Per	16126	M	238	0.61	3.64	1	0.48	1.50
SY Per	19931	SR	474	1.11	1.82	5	0.51	1.05
AU Aur	22796	M	400	1.46	2.87	1	0.64	1.51
R Ori	23165	M	377	2.37	4.07	14	0.31	2.53
R Lep	23203	M	438	1.65	0.05	71	0.24	0.44
S Cam	26753	SR	327	1.15	2.61	1	0.28	1.16
Y Tau	27181	SR	242	0.22	0.26	6	0.17	
V Aur	30449	M	349	1.72	2.99	1	0.33	1.45
CR Gem	31349	SR	250	0.54	1.36	1	0.27	
R CMi	34474	M	338	2.38	2.54	11	0.41	1.16
VX Gem	34859	M	391	1.87	3.13	9	0.03	1.68
T Lyn	41058	M	409	2.07	3.02	23	0.13	1.65
R Pyx	42975	M	369	1.70	2.50	11	0.36	1.20
UW Pyx	43123	LB	423	1.50	2.62	5	0.65	1.40
IQ Hya	45266	SR	397	1.77	2.84	15	0.52	1.49
W Sex	48316	SR	200	0.54	3.47	20	0.15	
V Hya	53085	L	532	2.15	−0.71	75	0.13	0.36
\ BH Cru	59844	M	421	1.71	1.49	54	0.65	0.83
RU Vir	62401	M	444	1.73	1.79	46	0.08	0.99
V Cru	63175	M	380	1.84	2.80	96	0.94	1.41
RV Cen	66466	M	447	1.25	1.40	87	0.82	0.83
V CrB	77501	M	358	2.05	1.27	48	0.04	0.67
RR Her	78721	SR	240	1.61	3.22	3	0.08	1.24
V Oph	80550	M	297	1.54	1.56	11	0.86	0.67
SZ Ara	84059	M	222	1.38	4.41	8	0.47	2.03
TT Cyg	96836	SR	118	0.38	1.95	2	0.21	
RS Cyg	99653	SR	417	1.40	1.00	4	0.50	0.66
WX Cyg	100113	M	399	1.48	2.29	1	0.78	
U Cyg	100219	M	460	2.18	1.11	7	0.59	0.74
V Cyg	102082	M	417	1.91	0.02	1	0.38	0.42
YY Cyg	105539	SR	388	0.51	2.58	1	0.73	
S Cep	106583	M	486	1.79	−0.10	1	0.38	0.44
RV Cyg	107242	SR	263	0.25	0.37	2	0.29	
RZ Peg	109089	M	439	3.12	2.48	2	0.44	1.35
ST And	116681	SR	328	1.65	3.37	16	0.28	1.65

Where there were more than five observations contributing to the mean K magnitude listed by Whitelock et al. (2000), or new SAAO photometry, these values were used. Otherwise K magnitudes were taken from the literature and particularly from the compilation by Gezari, Pitts & Schmitz (1999). The following references which were not cited by Gezari et al., or which are more recent, were also used: 2MASS (Cutri et al. 2003), DIRBE (Smith, Price & Baker

2004), Noguchi et al. (1981), Taranova & Shenavrin (2004), Chen et al. (1984), Gao, Chen & Zhang (1985), Kerschbaum, Lebzelter & Lazaro (2001), Sun & Zhang (1998), Chen et al. (1988),[1] Le Bertre et al. (2003).

Where necessary and practical observations from the literature were transformed to the SAAO system (e.g. Carter 1990; Carpenter 2001[2]). Most of the stars discussed here were sufficiently bright to be saturated in 2MASS and are quoted in the catalogue (Cutri et al. 2003) with large errors, these values were only used where little else was available. While there should be no problem with saturation of the DIRBE photometry (Smith et al. 2004), there is some risk of confusion with other sources in the large aperture. More importantly there is very little information available on the calibration or transformation for the DIRBE system; following Beverly Smith (private communication) we assume that a $K = 0$ mag star has a flux of 630 Jy. Although the DIRBE photometry was integrated over a period of days or weeks, a DIRBE *K* magnitude was only given the same weight as any other measurement when the mean was established for Table A3.

[1] The Chen et al. value for R Lyn ($K = 0.52$) was not used as it is inconsistent with other measurements.
[2] http://www.astro.caltech.edu/∼jmc/2mass/v3/transformations/

SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

Table A1. New IR photometry from SAAO.

This material is available as part of the online article from: http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-2966.2008.13032.x (this link will take you to the article abstract).

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