

THE LUMINOSITIES AND DIAMETERS OF MIRA VARIABLES FROM HIPPARCOS PARALLAXES*

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ABSTRACT

Hipparcos trigonometrical parallaxes of Mira-type variables have been combined with ground-based angular diameter measurements to derive linear diameters. Of eight stars with ground-based data, six have diameters indicating overtone pulsation whilst two, both with periods over 400 day, are pulsating in the fundamental.

Hipparcos parallaxes of 11 Miras have been combined with extensive infrared photometry to determine the zero-point of the Mira period-luminosity relation. Adopting the relation at K ($2.2\mu\text{m}$), since this is less likely to be subject to abundance effects than that at M_{bol} , leads to a distance modulus for the LMC of 18.6 mag with a uncertainty of slightly less than 0.2 mag.

A brief discussion is given of the preliminary analysis of the parallaxes of a much larger sample of Miras. Some consideration is given to possible problems in interpreting the Hipparcos data which arise because of the physical characteristics of the Mira variables. Finally the apparent low-luminosity of the carbon Mira, R Lep, implied by the Hipparcos results leads to an interesting problem in AGB evolution.

Key words: space astrometry; Mira variables; carbon stars; distance scale; angular diameters; infrared photometry; asymptotic giant branch.

1. INTRODUCTION

Miras are cool, long period, large amplitude variables. Their spectra are dominated by molecular absorption features and show hydrogen emission lines, as a result of shock waves, during certain phases of their pulsation cycles. Their periods are longer than 100 days and their visual light amplitudes in excess of 2.5 mag. The stars whose parallaxes are discussed

below have visual light variations, according to the General Catalogue of Variable Stars, of 5 to 10 mag, although their bolometric amplitudes are less than one mag. Examples of this type of star are found in the metal-rich globular clusters where they are the most luminous stars present. The Mira evolutionary phase is short lived, about 2×10^5 year, and is accompanied by heavy mass loss, typically between 10^{-6} and $10^{-5} M_{\odot} \text{yr}^{-1}$. We therefore understand the Miras to be at the very tip of the Asymptotic Giant Branch, probably in the so-called ‘superwind phase’. The Miras have potential as distance indicators among old metal-rich populations as they represent the maximum luminosity phase of such stars. They are best studied in the near-infrared as their flux distribution peaks between 1 and $2 \mu\text{m}$.

2. THE HIPPARCOS DATA

The authors have Hipparcos data on 180 Mira-like variables, but most of these have only been analysed in a superficial manner. The bulk of this paper, therefore, concerns 16 Miras for which early access to Hipparcos data was obtained and which have been examined in detail. These stars were selected, prior to any knowledge of their parallaxes, as potentially interesting objects. The details of this analysis are given by van Leeuwen et al. (1997). The sample of 16 comprises: 10 normal Miras of spectral type M, *o* Cet, R Tri, R Hor, U Ori, R Car, R Leo, S Car, RR Sco, T Cep and R Cas; one S-type, χ Cyg; one C-type, R Lep; two M-types with slowly decreasing periods, R Hya and R Aql, which may be undergoing He-shell flashes (Wood & Zarro 1981); one M-type star which has a double period, R Cen; the oxygen-rich symbiotic Mira, R Aqr, which is weakly interacting with a white dwarf and has been well studied at many wavelengths.

The Hipparcos parallaxes (π) and their errors (σ_{π}) are given in Table 1, together with the interstellar extinction at V (A_V), the extinction corrected mean $2.2 \mu\text{m}$ magnitude (\bar{K}_0), the number of *JHK* measurements (N) and the mean apparent bolometric magnitude (\bar{m}_{bol}). For the analysis a weighted mean of the Hipparcos parallax and that measured by Gatewood (1992) was used for R Leo. The

*Based on data from the Hipparcos astrometry satellite.

mean bolometric magnitudes were derived from near-infrared (*JHK*) photometry. For most of the Miras extensive observations have been made from the South African Astronomical Observatory (SAAO), but R Cas and T Cep are inaccessible from the south so for these stars data obtained in the Crimea was provided by Boris Yudin.

3. STELLAR RADII

For eight of the Miras with parallaxes Haniff et al. (1995) have measured angular diameters using optical interferometric techniques. These (ϕ) are listed in Table 1, together with their errors (σ_ϕ). Thus their linear radii can be calculated and compared with theoretical values. Such a comparison is shown in Figure 1 as a function of pulsation period. The theoretical predictions are shown for stars of mass 1.0 and 1.5 M_\odot pulsating in the fundamental and first overtone modes. The error bars on the observations represent the combined error on the radii and on the parallaxes.

The pulsation mode of the Miras has been a source of controversy for many years with good reasons for suggesting that the observed mode is the first overtone and other, also good, arguments for suggesting it must be the fundamental. Feast (1996) and Bessell et al. (1996) recently summarised the situation from very different viewpoints. Figure 1 can be interpreted as showing that most Miras with periods less than 400 day are pulsating in an overtone, while at least some of the stars with longer periods are pulsating in the fundamental.

4. PERIOD-LUMINOSITY RELATION

Period-luminosity (PL) relations have been established for Miras in the Large Magellanic Cloud (LMC) (Feast et al. 1989). These are of the form:

$$M_K = -3.47 \log P + \beta_1 \quad (1)$$

$$M_{\text{bol}} = -3.00 \log P + \beta_2 \quad (2)$$

where β_1 and β_2 are the zero-points which depend on the distance modulus of the LMC. These relations show only a small scatter of 0.13 mag in K and 0.16 mag in m_{bol} . It is with them that we compare the Hipparcos results. The relatively high errors on the parallaxes of the local Miras prevent an unbiased full solution for the period-luminosity relation. The slope of the PL relation is therefore assumed to be the same as in LMC, as given in Equations 1 or 2, and the zero-point is derived from the new data. The equations are solved in the following form, weighted according to the inverse square of the error on the parallax:

$$10^{0.2\beta_1} = 0.010 \pi^{0.2(3.47 \log P + K_0)} \quad (3)$$

$$10^{0.2\beta_2} = 0.010 \pi^{0.2(3.00 \log P + m_{\text{bol}})} \quad (4)$$

11 stars are used in the solution while the following are omitted: the two fundamental pulsators, χ Cyg and R Cas, the carbon star, R Lep, the double period star, R Cen, and the symbiotic, R Aqr. The following zero-points, and corresponding distance moduli

for the LMC, were derived:

$$K : \quad \beta_1 = 0.88 \pm 0.18 \text{ mag} \\ \text{LMC } (m - M)_0 = 18.60 \text{ mag}$$

$$M_{\text{bol}} : \quad \beta_2 = 2.88 \pm 0.17 \text{ mag} \\ \text{LMC } (m - M)_0 = 18.47 \text{ mag}$$

The K solution is probably to be preferred as it appears to be less subject to differences in metallicity (e.g. Feast 1996). The derived LMC distance modulus of 18.60 ± 0.18 is in good agreement with Feast & Catchpole's (1997) value of 18.70 ± 0.10 derived from the Cepheid variables, using a new calibration based on Hipparcos results.

The M_{bol} PL diagram is illustrated in Figure 2 where it can be seen that the two fundamental pulsators and the carbon star, R Lep, lie distinctly below the PL relation derived above. The K PL diagram, which is similar to Figure 2, is not illustrated here, but is shown in van Leeuwen et al. (1997).

5. LARGER DATA SET

The larger data set includes parallaxes and proper motions for 180 stars. Of these there are 115 oxygen- and 19 carbon-rich Miras for which there is also infrared photometry, either from SAAO or from the Crimea. It would be extremely useful to have infrared photometry for more of the northern stars; such measurements require a telescope with an aperture no more than 0.5 m. Even among the stars for which measurements have been made the light-curve coverage is often poor with only one or two observations per star. Note that rather few of these stars have parallaxes which are larger than their errors and quite a number of them have negative parallaxes, so the data set is not obviously a vast improvement over that discussed above and by van Leeuwen et al. (1997).

There is little purpose in listing numbers from a preliminary analysis that will undoubtedly be superseded in the near future. However, two points can usefully be made here. First, the PL zero-point estimated from the 103 oxygen-rich Miras with periods less than 400 days is very close to that derived for the 11 stars discussed above. Secondly, the zero-point derived from the 19 carbon-rich Miras is about 0.7 mag fainter than that derived from the short-period oxygen-rich stars. Thus R Lep is not the only carbon-rich Mira which lies below the PL relation. The consequences of this are discussed further in Section 7.

6. POSSIBLE PROBLEMS WITH THE PARALLAXES

Several Miras had a significant fraction of data rejected when the astrometric solutions were made. This can be seen from the parameter tabulated in Column 29 of the Hipparcos catalogue (H29). Among the stars discussed above are R Leo, χ Cyg and R Car, which had 10 per cent or more data rejected.

Table 1. *Observational Data.*

Star	π (mas)	σ_π	A_V (mag)	\bar{K}_0 (mag)	N	\bar{m}_{bol} (mag)	ϕ (mas)	σ_ϕ	logP (P in day)
o Cet	7.79	1.07	0.01	-2.50	98	0.70	33.6	3.5	2.521
R Tri	2.51	1.69	0.14	0.93	9	4.04			2.426
R Hor	3.25	1.08	0.02	-0.94	41	2.22			2.611
R Lep	3.99	0.85	0.08	-0.01	121	3.45			2.630
U Ori	1.52	1.65	0.23	-0.64	50	2.54	18.5	2.6	2.566
R Car	7.84	0.83	0.13	-1.35	77	1.74			2.490
R Leo	9.87	2.07	0.02	-2.55	50	0.69	37.4	2.3	2.491
S Car	2.47	0.63	0.35	1.84	34	4.65			2.175
R Hya	1.62	2.43	0.03	-2.48	51	0.66	28.7	3.3	2.590
R Cen	1.56	0.84	0.21	-0.72	67	2.38			2.737
RR Sco	2.84	1.30	0.20	-0.25	55	2.88			2.449
R Aql	4.73	1.19	0.23	-0.78	45	2.34	17.5	3.7	2.454
χ Cyg	9.43	1.36	0.14	-1.93	11	1.39	28.9	3.0	2.611
T Cep	4.76	0.75	0.11	-1.71	2	1.50	24.3	4.4	2.589
R Aqr	5.07	3.15	0.01	-1.02	120	2.26			2.588
R Cas	9.37	1.10	0.12	-1.80	13	1.40	24.9	2.9	2.633

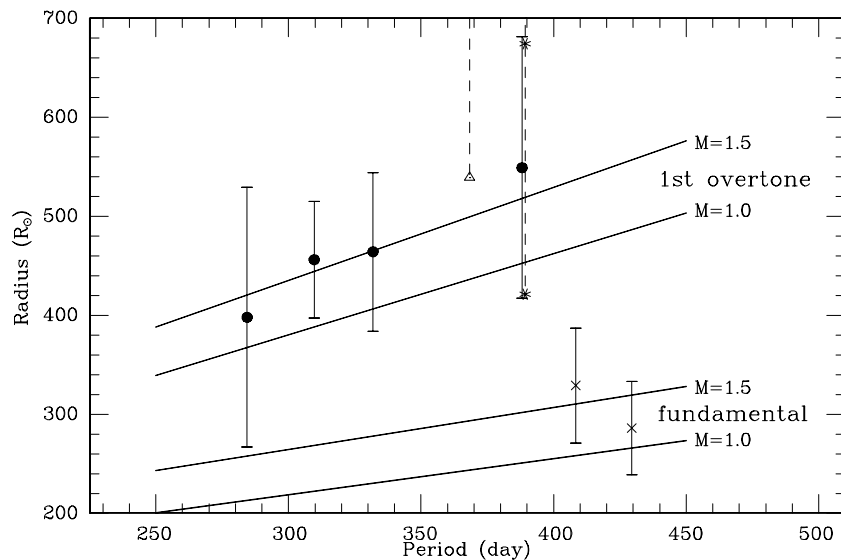


Figure 1. The Period-Radius relation for Mira variables. Filled circles: R Aql, R Leo, o Cet, T Cep; crosses: χ Cyg, R Cas. 1- σ error bars are shown. The triangle is the 1- σ lower limit for U Ori and the asterisks are the 1- σ and 2- σ lower limits for R Hya. The lines are the predicted relations for fundamental and for first overtone pulsation.

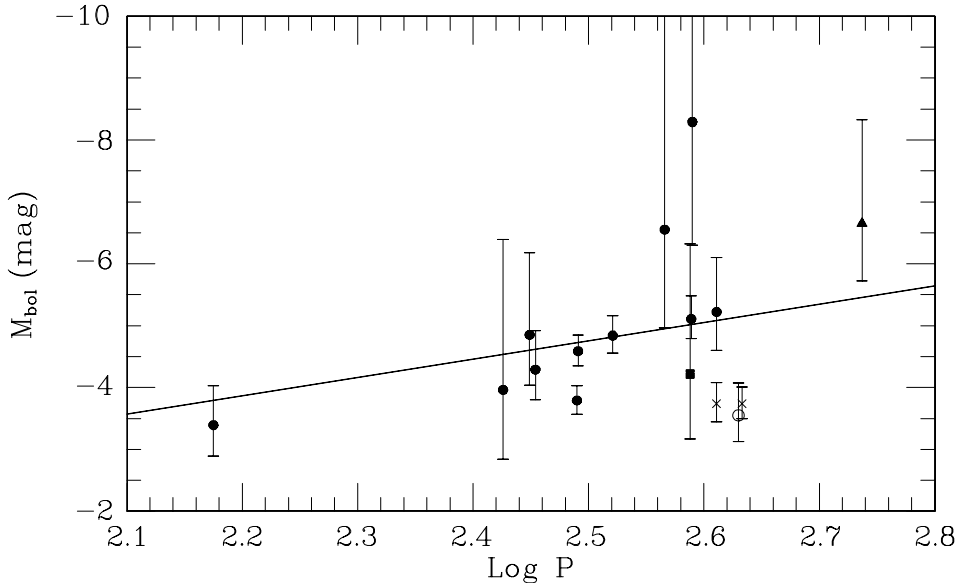


Figure 2. The M_{bol} - $\log P$ relation. Symbols: open circle: the carbon Mira, R Lep; filled square: the symbiotic Mira, R Aqr; filled triangle: the double period Mira, R Cen; crosses: the fundamental pulsators, χ Cyg and R Cas; filled circles the other Miras. The line represents the period-luminosity relation for the LMC assuming a distance modulus of 18.60 mag.

Several Miras have a rather poor ‘goodness of fit parameter’ as specified in Column 30 of the catalogue (H30), although χ Cyg is the only one among those discussed above.

χ Cyg is one of the fundamental pulsators with a faint bolometric magnitude. R Car is also faint in Figure 2 compared to the other stars although it was included in the solution for the PL zero-point. On the other hand the Hipparcos parallax of R Leo agrees well with that already published by Gatewood (1992). It is therefore not clear that the H29 and H30 parameters are indicating any real problem with the measured parallax. They may just indicate what we anticipated before the satellite flew, i.e. that it would be difficult for Hipparcos to measure some stars near minimum light and we should therefore expect some data rejection for these large amplitude pulsators.

χ Cyg is particularly faint, reaching minimum at $H_p = 12.09$ mag as listed in the Hipparcos Catalogue. In the next stage of the analysis we propose to avoid most of the minimum light problems by making a direct absolute magnitude calibration using the intermediate astrometric data as described by van Leeuwen (1997) and by van Leeuwen & Evans (1997). The minimum-light observations will be outweighed in such a solution by the other measurements. The common solution also offers better possibilities for recognising faulty observations.

Another problem is possible temporal changes in the light distribution across the disk of the Mira. The parallaxes of these Miras are actually smaller than their angular diameters. The parallaxes range from about 2 to 10 mas, while the diameters of the eight which have been measured are between 17 and 34 mas. We know that the Miras do not present uniform stellar disks; observations of R Leo made with the Fine Guidance Sensor on the HST, in two orthogonal directions, show that one axis exceeds the other

by 11 per cent and even bigger differences are found in some stars (Lattanzi et al. 1997). The cause of this is unknown as is the way it changes with time. It might be non-radial pulsation or it might be star spots resulting from large convection cells. Thus it is not yet clear if the effect will give us systematic errors in the parallax or increase the uncertainty of the measurement or even if it will have any effect at all. It is, however, clearly important to obtain more data on possible asymmetries and to investigate any possible effect on the parallaxes.

With the caveat that all these things need looking into in more detail, we do not have any strong reasons to feel there are any particular problems with the Hipparcos parallax data. In fact the Hipparcos parallaxes represent a remarkable set of data which will put our understanding of every aspect of the distance scale onto a new and firmer footing.

7. THE CARBON RICH MIRAS

The Hipparcos parallax of R Lep presents a problem which is discussed here very briefly. The parallax and infrared photometry imply a bolometric magnitude of $-3.6_{+0.42}^{-0.52}$ mag ($L = 2.2 \times 10^3 L_{\odot}$). This luminosity is faint even for the transition luminosity from oxygen to carbon stars, which in the LMC ranges from around -3.8 to about -4.8 , depending on mass and metallicity. Fainter transition luminosities are found only in the most metal-weak populations. Although we do not know the metallicity of R Lep, it has strong lines and seems unlikely to be metal deficient. In any case, stars near the transition luminosity are not normally large amplitude variables. Miras are normally a magnitude or so brighter; nearer the -5.1 mag ($L = 9 \times 10^3 L_{\odot}$) predicted for R Lep from the PL relation. As mentioned in Section 5 the parallaxes

of the other carbon Miras also imply faint absolute magnitudes for at least some of the stars.

We are therefore drawn to the possibility that R Lep actually has a luminosity close to that predicted from the PL relation, but that we have underestimated its apparent luminosity for some reason. For example such a situation could arise if R Lep was undergoing asymmetric mass-loss, and we were viewing the star through a dusty equatorial torus. This possibility has been discussed in more detail by Whitelock et al. (1997) who present infrared light-curves for R Lep and other carbon Miras. Several of these stars, including R Lep, have erratic long-term changes in their output which are reminiscent of the light-curves of R Corona Borealis (RCB) stars. This has been interpreted as the result of dust formation following non-periodic mass loss from the carbon Miras. If these stars eject dust in random directions, as the RCB stars apparently do, it will not explain the faintness of R Lep. If, however, they eject it preferentially in particular directions, such as in the equatorial plane, and it happens that we are viewing R Lep from such a preferential direction then its faintness might be understood as a consequence of circumstellar obscuration. On the other hand if some of the carbon Miras are actually considerably fainter than was previously thought then it will have repercussions for our understanding of dredge-up and of AGB evolution. Clearly this needs further investigation.

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