Astron. Astrophys. 317, 761–768 (1997)

ASTRONOMY AND ASTROPHYSICS

Determination of Miras temperatures from TiO and VO bands. Estimates of distances*

R. Alvarez and M.-O. Mennessier

GRAAL cc072, UPRESA 5024 CNRS/UMII, Université Montpellier II, F-34095 Montpellier Cedex 05, France

Received 25 January 1996 / Accepted 13 June 1996

Abstract. Effective temperatures are determined for a sample of 165 oxygen-rich Miras using indices related to molecular band strength of titanium oxide and vanadium oxide computed from narrow-band photometry observations. We find a clear although very scattered period–temperature relation which agrees with a previous one. Using a theoretical evolutionary track on AGB and assuming that the scatter around the period–temperature relation is due to mass differences, we can obtain a period–luminosity relation similar to the one observed in the LMC if the mass range is 0.8 to 2.6 $\mathcal{M}_{\odot}$. Effects of metallicity are discussed. The determined luminosities are used to calibrate distances that are compared to several other estimations.

Key words: stars: atmospheres – stars: distances – stars: fundamental parameters – stars: AGB and post-AGB

1. Introduction

Long-period variables of Mira type are excellent tracers of the history of the Galaxy as they mark with the other stars on the asymptotic giant branch a crucial stage in the evolution of stars with initial mass less than 8 $\mathcal{M}_{\odot}$. But the use of them in this field is made difficult by the uncertainties that exist as regards values of fundamental parameters: only little is known about temperatures, masses, radius and luminosities. On one hand, observations in a long time range are necessary to study variations (a typical period is 300 days for a Mira and furthermore there are changes in light curves from one cycle to the other); on the other hand, a realistic model of the physical structure from the stellar core to the stellar surface does not exist up to now and will be difficult to construct due to the extreme complexity of these stars.

Indeed, Mira atmospheres are very extended: models have to take account of sphericity effects and, more problematically, the LTE hypothesis may be invalid. The atmosphere is cold ($T_{\rm eff} < 4000$ K), which implies the apparition of a lot of lines of molecular bands: modeling requires a very large sum of molecular data among which some concerning important molecules are badly known. Moreover, these stars pulsate, and there does not yet exist a completely satisfactory theory explaining the real mechanism of pulsation. If it is now obvious that Miras are multi-pulsators, it is still unclear whether Miras pulsate mainly on fundamental or first harmonic, which has a great influence on the relationship between the fundamental physical parameters. Furthermore, there is a strong stellar wind with high mass-loss rates which could show irregular behaviour with time.

Some authors have nevertheless made important progress in some fields like theoretical models of pulsation (Fox & Wood 1985; Tuchman et al. 1993), dynamical models of atmospheres (Bowen 1988; Bessel et al. 1989) or models of late-type stellar photospheres (see Gustafsson & Jørgensen 1994 for a review).

In this paper, we have tried to determine some fundamental parameters from narrow-band photometry observations (Lockwood 1972) which were obtained during a period of more than two years and for nearly 300 Miras. From these photometric observations (described in Sect. 2) we have computed indices related to molecular band strengths of titanium oxide (TiO) and vanadiun oxide (VO) which are used as temperature indicators (Sect. 3). A period–temperature relation (Sect. 4) is determined which agrees well with a previous one (Glass & Feast 1982). The likely too simple way of explaining the scatter of this relation only by the distribution of mass is considered (Sect. 5) before luminosity and distance estimates are proposed for 165 Miras of the sample. These distances are compared with other estimates. The procedure allows us to check the reliability of our calibrations (Sect. 6).

2. Observations

Lockwood (1972) observed 292 M– and S–type Mira variables from 1969 to 1971 at the Kitt Peak National Observatory, with a five-colour narrow-band photometric system. He obtained 1795 individual sets of five-colour measurements, at different phases, and, for some stars, during several cycles. The photometric sys-

Send offprint requests to: R. Alvarez, alvarez@graal.univ-montp2.fr

* Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 1. Properties of the five-colour system

Filter designation	Peak wavelength	Half-power bandwidth	Function
78	7818 Å	90 Å	2–3 and 3–4 bands of TiO γ system
87	8777 Å	82 Å	pseudo-continuum
88	8884 Å	114 Å	0–0 band of TiO δ system
104	10351 Å	125 Å	continuum
105	10506 Å	100 Å	Δv=0 transition of VO A–X system

tem used was based on Wing's system (Wing 1967a), which measured 27 colours. Lockwood reduced the number of bandpasses to five: two continuum or pseudo continuum regions, one VO and two TiO bands. Table 1 gives properties of the five-colour system.

The significance of the Lockwood measurements lies in the fact that only few sets of regular observations of an important number of Miras are available. Moreover, the narrow bands allow a precise study of TiO and VO behaviour with phase. The presence of these molecules in the atmosphere depends strongly on temperature. So it is possible to use TiO and VO indices to obtain temperature estimates.
Filter 104 measures a region relatively free of molecular absorption. Wing (1967b) considered this bandpass to give a reliable measurement of the continuum. Filter 87 should have been a continuum measurement too, but this band becomes contaminated by TiO bands in the later M stars. This effect makes the continuum measurement very unreliable and has prevented a colour temperature determination as Lockwood expected from the 87−104 index. Filters 78 and 88 measure several bands of TiO as indicated in Table 1, and filter 105 measures the Δv=0 transition of the VO A-X system.

The median standard errors are less than 0.025 mag. The effect of interstellar and circumstellar reddening is supposed to be small in the near-infrared around 10 000 Å. But this hypothesis, especially concerning the circumstellar extinction, might be erroneous for some stars and we must be aware of it.

3. TiO and VO indices as temperature indicators

Gray and Johanson (1991) showed that the ratio of line depths for two spectral lines can be used to determine stellar temperature with a very high precision. Similarly, it is possible to use two indices linked with two depths of molecular band heads as temperature indicators.

The first one, 78−88, is proportional to the ratio between two different band heads of TiO. This index is a good indicator for temperatures above 3000 K. For lower temperatures, the TiO bands begin to saturate. 78−88 should depend not too strongly on metallicity in so far as it concerns the ratio of two bands of the same element (however saturation effects may make this untrue). The second index, 105−104, is related to a VO band and a continuum point. It depends strongly on temperature below 3000 K when the VO molecules begin to appear. This index might be sensitive to the vanadium abundance. These two molecular indices complement each other as temperature indicators.

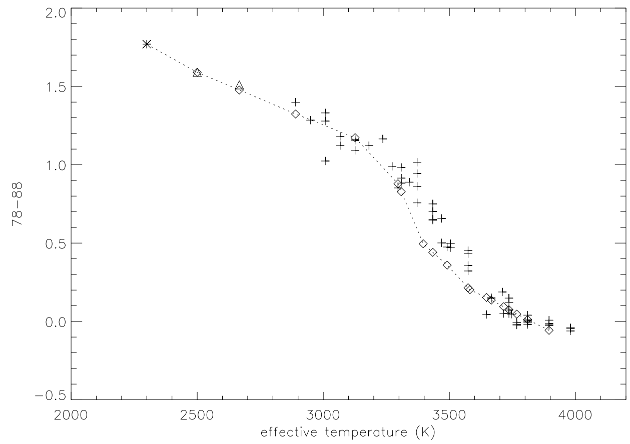

Fig. 1. The 78−88 index as a function of effective temperature. Diamonds are indices measured on averaged spectra observed by Fluks et al. (1994). Crosses are standard red giant indices taken from Lockwood (1972). R Leo and U Her indices at phase 0.44 and 0.61 respectively are represented by triangles and R Cas index at phase 0.57 is represented by an asterisk (see text)

In order to calibrate the 78−88 and 105−104 indices as a function of temperature, we have used averaged observed spectra of red giants (Fluks et al. 1994). These authors have obtained intermediate resolution long-slit spectra (3800 Å$\leq \lambda \leq$ 9000 Å) with the ESO 1.52 m telescope for a sample of 97 M giant stars.

Fluks et al. averaged the spectra for subtypes of the Case and MK classification systems from M0 to M10 and they fitted the results to photospheric synthetic spectra obtained with the model atmosphere code of Plez et al. (1992) in order to derive an effective temperature for each spectral type. They found an effective temperature–spectral type relationship closed to that of Ridgway et al. (1980). Since there is no non-variable M giants of subtypes M9 and M10, these subtypes have been based on spectrum of R Leo and U Her respectively which are Mira variables close to their minimum luminosity.

To each averaged spectrum representative of the spectral subtypes of the Case and MK classification (that is to say 18 different spectra), we have applied the filters described above. Given the fact that the displayed spectral region ends around 9000 Å, we have only obtained results for the 78−88 index. The characteristics of the different filters are given by Lockwood and Wing (1971). The zero point of the photometric system is defined by I(104)=0.00 mag for α Lyr. The zero points of the other bands than 104 are not mentioned explicitly but the set of colours of Vega is given. So, the filters have been calibrated on the basis of a spectrum of α Lyr. Figure 1 shows 78−88 as a function of temperature.

The diamonds are the indices measured on the 18 averaged spectra and the dashed line represents the (78−88)–$T_{\rm eff}$ relationship we use subsequently. The asterisk is a point we have added for the calibration; it represents R Cas. Indeed, in Lockwood's sample of Mira stars, the index 78−88 has a maximum value (1.77) for R Cas at minimum (phase 0.57). On the other hand, the spectrum which Fluks et al. take as representative of spectral type M10 is that of U Her, a Mira star which Lockwood classified as M9 at minimum (in his classification spectral type M10 is only represented by R Cas at minimum). This expresses the unreliability of the spectral classification for these very evolved stars. However, we have decided to add the point (78 − 88 : 1.77 ; $T_{\rm eff}$: 2300 K) which represents R Cas at minimum in order to cover all the data from Lockwood's sample. The effective temperature of 2300 K has been taken to keep the progression: M7∼3100 K, M8∼2900 K, M9∼2700 K, M10∼2500 K.

The two triangles represent R Leo and U Her taken from Lockwood's data at phase 0.44 and 0.61, respectively, when the 78−88 index agrees well with the one deduced from the spectrum of the two stars (the M9 and M10 spectra).

The crosses are the indices of 61 standard red giants observed by Lockwood in the same five-colour system as the Miras. He gave them a spectral type (K5 to M8), which corresponds to a temperature using the effective temperature–spectral type relation of Fluks et al. The observations agree well with the (78−88)–$T_{\rm eff}$ relationship, given the uncertainties in the spectral type.

New temperatures are obtained for these standard stars (plus R Leo, U Her and R Cas as they complete the list beyond M8) by using the (78−88)–$T_{\rm eff}$ relationship of Fig. 1. The 105−104 measurements of the stars are then plotted as a function of effective temperature (Fig. 2). A fit by a polynomial function gives the behaviour of 105−104 as temperature indicator. We are conscious that the results might be uncertain especially for low temperatures (only three points below 2800 K), but temperatures are very poorly known for very evolved stars in general, and a considerable ambiguity cannot be avoided at present.

We have thus arrived at a $T_{\rm eff}$ calibration of the sequence of stars in the 78−88/105−104 plane.

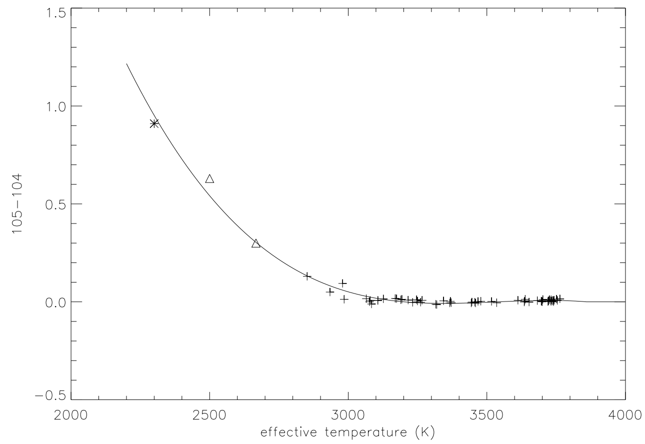

Fig. 2. The 105−104 index as a function of effective temperature. Symbols as Fig. 1

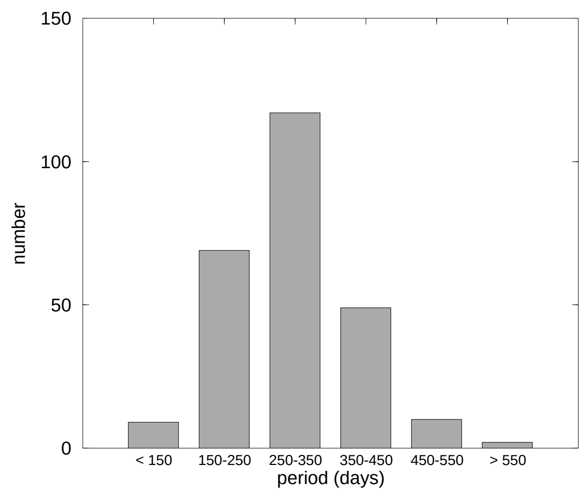

Fig. 3. Distribution of periods (256 Miras)

4. Application to Miras. Period–temperature relationship

4.1. Determination of temperatures

Lockwood observed 292 stars among which 256 are M– or MS–Miras; the others are classified S–Miras or semi-regular variables. These oxygen-rich Miras have been observed at several phases, sometimes in different cycles, to give 1501 sets of five-colour measurements. Figure 3 shows the distribution of periods of the sample, which perfectly corresponds to the distribution of the M–Miras taken in the General Catalogue of Variable Stars (Kholopov 1985, 1987). The stars have been preferably observed near maximum and minimum of light curves.

All the data (1501 points) are plotted on the plane 78−88/105−104 plane (Fig. 4). The curve calibrated in temperature as determined in Sect. 3 is also drawn. The data follow the curve relatively closely in general, but they are strongly scattered. This is due to the fact that a Mira atmosphere is much more complex than that of a non-variable star.

Among the 256 M–Miras, 93 are observed more than 5 times (group I) and 93 between 3 and 5 (group II). Miras with one or two observations are not taken into account subsequently. In order to make a determination of temperatures for a number of stars as large and homogeneous as possible, we have fitted the observed indices for each individual Mira as a function of phase φ by sine curves:

$$index = a_0 + a_1 \sin[2\pi(\varphi - a_2)] \quad (1)$$

For group II, we have reduced the 3 free parameters to 2: a_0 and a_1; a_2 is taken equal to 0.25 so the maximum is fixed at φ = 0.5. We have only kept the Miras which have observed indices distributed in a phase range larger than 0.3. This allows us to fit properly the indices and to obtain values of 78−88 and 105−104 at estimated minimum and maximum for a large sample. The 78−88 index saturates at about 1.8 so we adopted this value when the fit gives a greater estimate. Similarly, we set

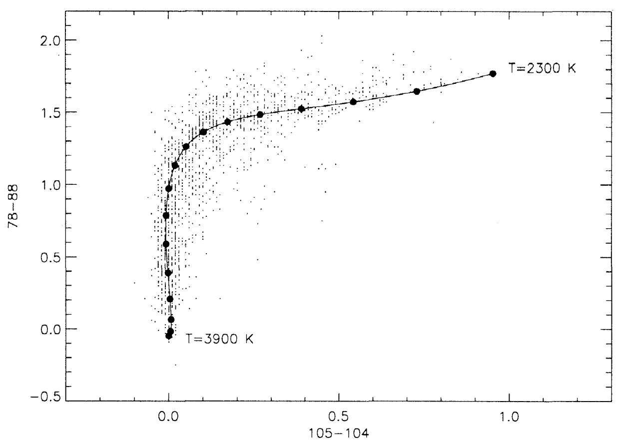

Fig. 4. Location of observed indices for all Miras of the sample at all phases. Fill circles are separated by 100 K

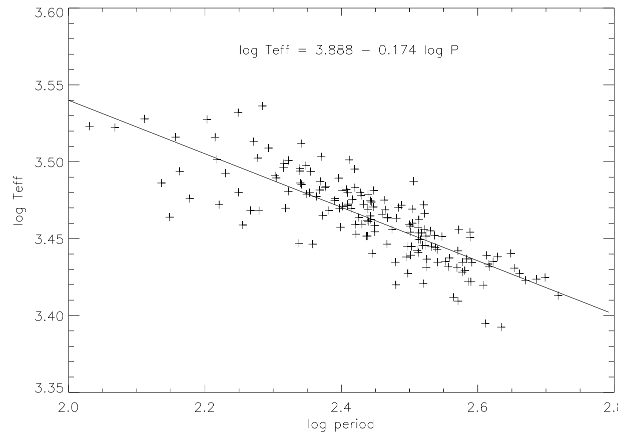

Fig. 5. Period–temperature relationship

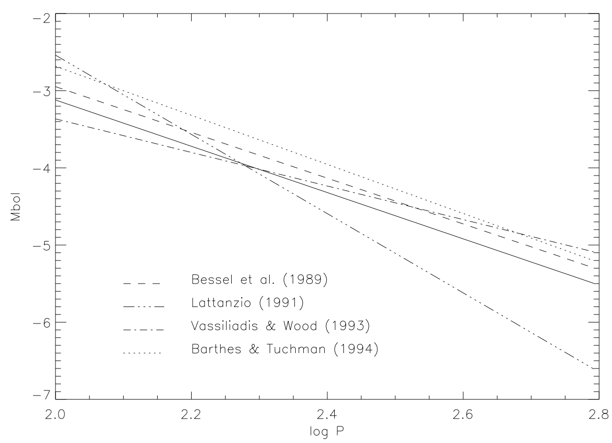

Fig. 6. Bolometric magnitude as a function of period for different theoretical evolutionary tracks on the AGB (with Z=0.02 and $\mathcal{M}$=1.5 $\mathcal{M}_\odot$) and using the period–temperature relation of Eq. (2). The solid line is the period–luminosity relation determined by Feast et al. (1989) for the LMC

min(105−104) = 0.0 when a lower result is obtained. At last, we exclude the stars for which:

$$\max(78-88)_{\rm fit} > \max(78-88)_{\rm observed} + 0.4$$
$$\min(78-88)_{\rm fit} < \min(78-88)_{\rm observed} - 0.4$$
$$\max(105-104)_{\rm fit} > \max(105-104)_{\rm observed} + 0.3$$
$$\min(105-104)_{\rm fit} < \min(105-104)_{\rm observed} - 0.3$$

Among the 186 Miras with a number of observations greater than 3, 165 finally remained.

The resulting values of 78−88 and 105−104 at minimum and maximum are represented by points which often scatter from the curve of Fig. 4. Indeed, each index does not separately give the same temperature. We nevertheless choose to fix a temperature for each couple of values by taking the nearest point of the curve, i.e. the perpendicular projection. The distance between the representive point at minimum or maximum and its projection on the curve gives an uncertainty estimate on temperature. Table 2 gives, for each star, the period, the group, the averaged temperature $T_{\rm eff}$, the uncertainty on $T_{\rm eff}$ and the amplitude of variation ($T_{\rm max} - T_{\rm min}$). The averaged temperature used is $1/3\,T_{\rm max} + 2/3\,T_{\rm min}$. Indeed, comparison between static and dynamical atmosphere models (Tuchman et al. 1979) shows that is a good approximation of the static temperature. Using the straight mean temperature does not change the results appreciably. We note that the mean temperature amplitude is 640 K. The Mira models developped by Bessell et al. (1989a) predict an effective temperature variation of 680 to 770 K.

4.2. Period–temperature relationship

Figure 5 shows $\log T_{\rm eff}$ versus $\log P$ for the 165 Miras of Table 2. There is a clear though scattered linear relation.

A least-square polynomial fit gives:

$$\log T_{\rm eff} = 3.888 - 0.174 \log P, \qquad \sigma = 0.016, \qquad (2)$$

σ being the standard deviation.

For 121 Miras of the Galaxy, Glass & Feast (1982) obtained:

$$\log T_{\rm bb} = 3.862\,(\pm 0.030) - 0.177\,(\pm 0.012) \log P \qquad (3)$$

$T_{\rm bb}$ is the temperature of the best black body fit they have made of JHKL observations. These authors have argued that $T_{\rm bb}$ is similar to $T_{\rm eff}$. The scatter (σ = 0.019) around their regression line is comparable to ours (cf their Fig. 2).

It is very satisfactory to see that both relations are similar whereas the two methods to determine temperature are totaly different. This indicates that the temperatures obtained here, despite the uncertainty on the method, are globally reliable. It seems clear that the temperature is correlated with the period, but the large scatter prevents us from giving a unique temperature for a given period.

5. Luminosities and mass range

5.1. Mass as the origin of the scatter in the period–temperature relationship

The period–temperature (PT) relation is very scattered, and the error bars are not always large enough to explain this fact. The period does not depend only on temperature but on mass and metallicity too. Furthermore, there may be different relations depending whether the Miras pulsate mainly in the fundamental or the first harmonic.

Mira variables are supposed to obey to a period–luminosity (PL) relation (see, e.g., Feast et al. 1989). The PT and PL relations might be related with the help of a theoretical evolutionary track on AGB if some assumptions are made about masses and metallicities.

Different evolutionary tracks on the AGB described by $M_{\rm bol}$=f $(T_{\rm eff}, \mathscr{M}, Z)$ relations where $\mathscr{M}$ is the mass and Z is the metallicity have been considered: Lattanzio (1991), Vassiliadis & Wood (1993), Fox & Wood (1982) cited in Bessell et al. (1989b) and Barthès & Tuchman (1994 and private communication). The period–luminosity relations that are obtained if the temperature is replaced by the period from Eq. (2) are plotted in Fig. 6. All have been computed with Z = 0.02 and $\mathscr{M}$=1.5 $\mathscr{M}_\odot$.

On the same graph the period–luminosity relation observed by Feast et al. (1989) for the Miras of the Large Magellanic Cloud (a distance modulus of 18.47 has been adopted) has been plotted. Stars of the LMC are supposed to have a metallicity smaller than those of the Galaxy. Nevertheless, Whitelock et al. (1994) showed that a single PL relation is obeyed by Miras in the LMC, the Galactic globular clusters and the solar neighbourhood. They argue that there is no justification for making theoretical metallicity corrections to the observed PL relation. So, the choice to use the PL relation observed in the LMC without correction has been made here.

Some of the PL relations determined above (the ones calculated with Bessell et al. and Barthès & Tuchman tracks) have a slope similar to the relation observed by Feast et al. This is always the case even with another mass than 1.5 $\mathscr{M}_\odot$. This suggests that the dispersion of masses may be introduced as the origin of the scatter in the period–temperature relationship.

We have made the following strong assumptions:

– the scatter of the PT relation is only due to dispersion of masses. The effect of metallicity which certainly exists is not taken into account

– there is a linear relation between $T_{\rm eff} - T_{\rm fit}$ and mass, where $T_{\rm eff}$ is the temperature of the Mira determined in Sect 4., and $T_{\rm fit}$ is the temperature obtained with Eq. (2):

$$\mathscr{M} = (\mathscr{M}_{\rm min} - \mathscr{M}_{\rm mean}) \frac{T_{\rm eff} - T_{\rm fit}}{(T_{\rm eff} - T_{\rm fit})_{\rm min}} + \mathscr{M}_{\rm mean} \quad (4)$$

– the Miras follow the evolutionary track cited by Bessell et al. (for solar abundance):

$$M_{\rm bol} = \frac{(\log T_{\rm eff} - 3.697 - 0.091 \log \mathscr{M})}{(0.0631 - 0.025 \log \mathscr{M})} \quad (5)$$

The two free parameters $\mathscr{M}_{\rm min}$ and $\mathscr{M}_{\rm mean}$ of the linear relation can be found by requiring a period–luminosity relation in agreement with the Feast et al. one. A mean mass $\mathscr{M}_{\rm mean}$ of 1.7 $\mathscr{M}_\odot$ and a minimum mass $\mathscr{M}_{\rm min}$ (which corresponds to the smallest algebraic value of $T_{\rm eff} - T_{\rm fit}$) of 0.8 $\mathscr{M}_\odot$ give the following PL relation which is the best approximation in the range log P=[2.0, 2.6]:

$$M_{\rm bol} = 3.15 - 3.12 \log P \quad (6)$$

The PL relation of Feast et al. for oxygen-rich Miras of the LMC is:

$$M_{\rm bol} = 2.88\,(\pm 0.57) - 3.00\,(\pm 0.24) \log P \quad (7)$$

The absolute bolometric magnitudes we obtained are thus very close to those given by the Feast et al. relation. With these parameters $\mathscr{M}_{\rm min}$ and $\mathscr{M}_{\rm mean}$, the maximum mass of the sample is 2.6 $\mathscr{M}_\odot$. The mass range so determined is not striking for oxygen Miras with period less than 550 days according to classical models.

5.2. Effect of metallicity

If, despite the results of Whitelock et al., thick disk and halo Miras follow different PL relations because of metallicity—as it is the case for Cepheids (Nemec et al. 1994)—, the absolute bolometric magnitudes determined previously are certainly not reliable for a large part of the sample. There is also an effect on the mass range.

For halo Miras, Eq. (5) is not adapted and another evolutionary track on the AGB for low-metallicity stars is needed. Such a track is given in Bessell et al. (1989b). Using that, we have computed new masses in the same way as described previously. We find low masses, which is not surprising for halo stars, but probably too low (the mean mass is 0.4 $\mathscr{M}_\odot$). This may be due to an irrelevant period–temperature relationship. Indeed, if there is a different PT relation for each population (metal-poor and metal-rich Miras), Eq. (2) is certainly not suitable for halo stars, the less numerous population.

For thick disk Miras, Wood (1990), extrapolating results from pulsating theory, argues that the local stars are intrinsically fainter by 0.44 mag if the metal abundance of Miras in the LMC is taken to be 1/4 $Z_\odot$. The necessary mass range to obtain a PL relation 0.44 fainter is 0.5 to 2.0 $\mathscr{M}_\odot$ with a mean mass $\mathscr{M}_{\rm mean}$ equal to 1.3 $\mathscr{M}_\odot$. It is, however, difficult to quantify how much local Miras are really fainter than LMC Miras and the value of 0.44 mag is dependent on an assumption on pulsation mode (fundamental in this case).

6. Distance estimates

6.1. Method

Lockwood has measured apparent magnitudes in 104 filter which is a continuum region at several phases for each star. Individual mean apparent magnitudes $m104$ are calculated. We take as average value two-thirds of the maximum plus one-third

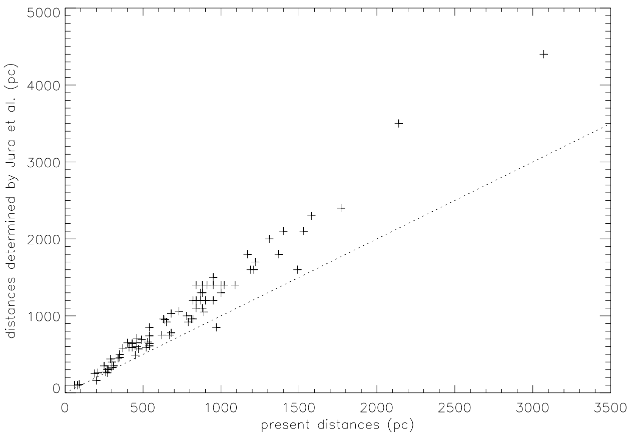

Fig. 7. Comparison between our preliminary distances (see Sect. 6.1) and those based on infrared photometry and the K–band period–luminosity relationship. Dotted line is the one-to-one line

Table 3. Trigonometric parallaxes. The first value for each star is taken from Jenkins (1963) and the second from Van Altena et al. (1991)

Name	Parallax (arc Sect.)	Distance (pc)
R Cnc	0.012 ± 0.006	83 (56-167)
	0.0093 ± 0.0053	108 (68-250)
T Cas	0.026 ± 0.011	38 (27-67)
	0.0286 ± 0.0051	35 (30-43)
o Cet	0.013 ± 0.005	77 (56-125)
	0.0257 ± 0.0051	39 (32-49)
R Leo	0.012 ± 0.009	83 (48-333)
	0.0129 ± 0.0111	78 (42-556)

of the minimum to be consistent with the parameters determined previously. The bolometric correction $m_{\rm bol} - m104$ as a function of temperature is obtained by estimating the flux integral and by applying the 104 filter on the photospheric synthetic spectra (M0 to M10) given by Fluks et al. The filter 104 has been calibrated with a spectrum of Vega, as the zero point of the Lockwood system is defined by m104=0.00 mag for α Lyr. The resulting apparent bolometric magnitudes are listed in Table 2.

The absolute bolometric magnitudes determined in Sect. 5 are based on the Feast et al. relation. They might be fainter if a metallicity correction is needed. We rely on known trigonometric parallaxes taken from the catalogues by Jenkins (1963) and Van Altena et al. (1991) to examine if such a correction must be made. Unfortunately, in our sample only R Cnc, T Cas, *o* Cet and R Leo have measured parallaxes (Table 3).

If we suppose no metallicity correction of the period–luminosity relation, we find R Cnc at 250 pc, T Cas at 290 pc, *o* Cet at 100 pc and R Leo at 120 pc. These distances seem too large. Thus, we decide to adopt a correction in order to obtain smaller distances. We suppose that the absolute bolometric magnitudes determined in Sect. 5.1 are 0.9 mag fainter in order to derive a distance of 80 pc for R Leo. We obtain by this way "preliminary" corrected distances, in the sense that we apply the correction to all the Miras of the sample. The choice of R Leo to calibrate the period–luminosity relation has been made for the two following reasons: 1. its Jenkins parallax is well confirmed by Van Altena et al. (it is not the case for *o* Cet), 2. Hipparcos will certainly provide a good parallax (σ_ϖ/ϖ less than 20%) for R Leo; it may not be the case for R Cnc and T Cas (Turon, 1995). So, as soon as Hipparcos results will be available, it will be easy to see if the distances we propose need a scale correction by comparing with R Leo parallax.

6.2. Comparisons with other distance estimates

Figure 7 shows the comparison between our preliminary distances and those determined using infrared photometry and the K–band period–luminosity relationship of Feast et al. (Jura & Kleinman 1992; Jura et al. 1993).

The graph representating both distances shows a small dispersion. The estimations by Jura et al. are systematically greater than ours by a factor of 1.4, approximatively. Since they used the K–band period–luminosity relation, it is not surprising to find such a small dispersion. The systematic factor is due to different metallicity correction: as proposed by Wood (1990), they assumed that the local stars are intrinsically fainter in K by 0.25 mag than the Magellanic Cloud stars. This correction in the K band corresponds to 0.44 mag in $M_{\rm bol}$ while we apply a correction of 0.9 mag to determine our distances. Furthermore Jura et al. consider a mean absolute K magnitude but do not systematically use the mean apparent K magnitude because data at various phases are not always available; this may induce an overestimate of their distance moduli. Only more numerous precise parallaxes ($\sigma_\varpi/\varpi < 0.5$) could provide a good calibration and give reliable absolute distances.

Figure 8 shows the comparison with distances determined by Luri et al. from a maximum likelihood method applied to kinematical data and visual magnitudes (Luri et al. 1996a). These authors find that Miras belong to different galactic populations: principally to the thick disk but some are probably halo stars (Mennessier et al. 1995).

The agreement is acceptable for the thick disk stars, despite the fact that both methods and sets of data are totally different. Discrepancies might be due to the uncertainty in the mean $m104$ determination (some stars have different minimum or maximum values for different cycles; it is the case for *o* Cet). Moreover, the interstellar or circumstellar extinction is not taken into account in our study while a correction for the first one is included in the procedure of Luri et al. The distances are also dependent on the metallicity correction and, as with the distances determined by Jura et al., there might be a systematic scale error. Hipparcos trigonometrical parallaxes will clear up some of these points and improve the calibration of the period–luminosity relation by furnishing several stars with known distances.

The estimations of distances are however discrepant for Miras classified as extended thick disk or halo stars by Luri et al (1996b). These stars are indicated by square symbols on Fig. 8. This expresses the fact that, if the metallicity correction of 0.9 mag seems appropriate to the disk Miras, it is not the case for the halo Miras which have a metallicity closer to the LMC ones. If we use the magnitudes without correction for the halo Miras,

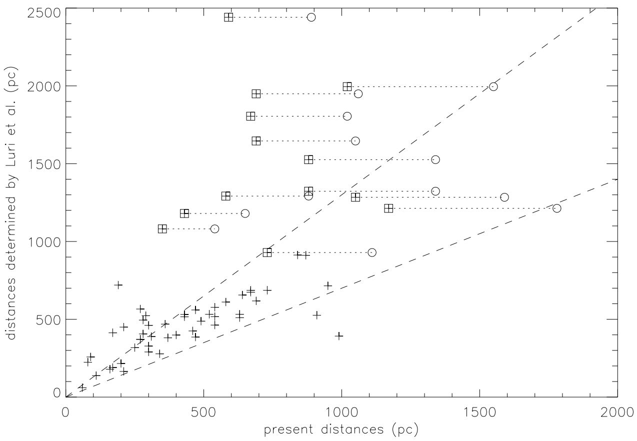

Fig. 8. Comparison between our preliminary distances (see Sect. 6.1) and those of Luri et al. (1996b) using the maximum likelihood method. Dashed lines give limits of 30% error. Square symbols indicate Miras classified as extended thick disk or halo stars by Luri et al. Circles indicate the new distances without metallicity correction (see text)

then their distances are in better agreement with those of Luri et al. (these new distances are indicated by circles in Fig. 8). Some halo Miras have still under-estimated distances.

All Miras classified as halo stars by Luri et al. have short periods. This is consistent with the fact that metal-poor Miras certainly belong to the group of variables with periods less than 200 days (Hron 1991). So, we made the assumption that also Miras of our sample with short period but not belonging to the sample of Luri et al. are halo stars. The absolute bolometric magnitudes and the definitive distances listed in Table 2 take into account the following:

– Miras with period greater than 200 days are supposed to be thick disk stars. There is a metallicity correction of 0.9 mag in bolometric magnitudes determined in Sect. 5.

– Miras with period less than 200 days might be halo stars. The $M_{\rm bol}$ listed are those determined in Sect. 5 without correction. An 'H' (halo) in the last column of Table 2 identifies Miras belonging to the halo stars group of Luri et al. and an 'SP' (short-period) those which are not in their sample.

This value of 200 days is of course somewhat arbitrary but it enables us to point out which values must be taken with great caution.

6.3. Choice of the calibration star. MS Miras

By taking R Leo at 80 pc as calibration star, we find R Cnc at 170 pc, T Cas at 190 pc and *o* Cet at 60 pc. For R Cnc, this distance is compatible with the range of distance deduced from trigonometric parallaxes (Table 3); for *o* Cet, it agrees with the parallax given by Jenkins. These results and the agreement between our distances and those determined from kinematical data and visual magnitudes justify a posteriori the choice of R Leo as calibration star for disk stars.

For T Cas, the distance is far outside intervals defined by error bars. Jura et al. give T Cas at 250 pc, which is consistent with the value of 190 pc we found when the systematic factor discussed above is taken into account. So, the discrepancy, if the trigonometric parallax is confirmed, is not due to an error in apparent magnitude $m104$ but it may be due to the fact that T Cas does not follow the same period–luminosity relation as the disk Miras. Wing & Yorka (1977) classified T Cas as an MS–Mira due to the presence of ZrO bands. Moreover, Luri et al. (1996b) find that T Cas could belong to a group of kinematically peculiar Miras. So, we decide to identify all stars classified as the same type with an 'MS' in Table 2: those stars might not obey the same period–luminosity relation as the others Miras and the distances might be not reliable.

7. Conclusions

We have determined effective temperature estimates for 165 Miras of the Galaxy using TiO and VO molecular band strengths as temperature indicators. We derived a clear although scattered period–temperature relation, which agrees well with the relation determined by Glass and Feast (1982).

From this period–temperature relation and with the help of a theoretical evolutionary track on the AGB, it is possible to obtain a period–luminosity relation similar to the one determined by Feast et al. (1989) for the Miras of the Large Magellanic Cloud, with the hypothesis that the scatter of the PT relation is due to a distribution in mass. Mass range and absolute bolometric magnitudes are then determined. According to the results of Whitelock et al. (1994), Miras obey to a single period–luminosity relation whatever their metallicity. If this is not the case, the possible effect of metal abundance on mass range determination must be emphasized.

From Lockwood's observed apparent magnitudes, distances are proposed for the sample of Miras. We rely on the trigonometric parallax of R Leo to determine a metallicity correction to the PL relation. We compare the distances with those obtained by Jura et al. (1992, 1993) and Luri et al. (1996b), the latter authors using a completely different method. Our estimates are smaller than the distance of Jura et al. due to different metallicity corrections. However, the very small dispersion in the relation ($d_{\rm our}$, 1.4 $d_{\rm Jura}$) is remarkable and enhances the necessity to increase the number of good trigonometric parallaxes to improve the distance calibration. The agreement with the second estimates is good for Miras classified as thick disk stars. The discrepancy for halo stars might confirm that Miras of different metallicities may follow different PL relations. Hipparcos will provide good trigonometric parallaxes for some of these Miras, which will enable improvements of the calibration.

Acknowledgements. We thank X. Luri, J. Torra, F. Figueras and D. Barthès for fruitful discussions and for providing some of their results, and B. Plez for giving a spectrum of Vega. We are also grateful to B. Gustafsson for useful comments as a referee.

References

Barthès D., Tuchman Y., 1994, A&A 289, 429
Bessell M.S., Brett J.M., Scholz M., Wood P.R., 1989a, A&A 213, 209

Bessell M.S., Brett J.M., Scholz M., Wood P.R., 1989b, A&AS 77, 1
Bowen G.H., 1988, ApJ 329, 299
Feast M.W., Glass I.S., Whitelock P.A., Catchpole R.M., 1989, MNRAS 241, 375
Fluks M.A., Plez B., Thé P.S., et al., 1994, A&AS 105, 311
Fox M.W., Wood P.R., 1985, ApJ 297, 455
Glass I.S., Feast M.W., 1982, MNRAS 199, 245
Gray D.F., Johanson H.L., 1991, PASP 103, 439
Gustafsson B., Jørgensen U.G., 1994, A&AR 6, 19
Hron J., 1991, A&A 252, 583
Jenkins L.F., 1963, General Catalogue of Trigonometric Stellar Parallaxes, Yale Univ. Obs., New Haven
Jørgensen U.G., 1994, A&A 284, 179
Jura M., Kleinmann S.G., 1992, ApJS 79, 105
Jura M., Yamamoto A., Kleinmann S.G., 1993, ApJ 413, 298
Kholopov, P.N. (ed.), 1985, 1987, General Catalogue of Variable Stars, Fourth Edition, Nauka Publ. House, Moscow
Lattanzio J.C., 1991, ApJS 76, 215
Lockwood G.W., 1972, ApJS 24, 375
Lockwood G.W., Wing R.F., 1971, ApJ 169, 63
Luri X., Mennessier M-O., Torra J., Figueras F., 1996a, A&A in press
Luri X., Mennessier M-O., Torra J., Figueras F., 1996b, A&A in press
Mennessier M-O., 1981, A&A 93, 325
Mennessier M-O., Luri X., Figueras F., Torra J., 1995, Miras and galactic populations. In: R.S. Stobie, P.A. Whitelock (eds.) Proc. IAU Coll. 155, Astrophysical applications of stellar pulsation, A.S.P. Conference Series Vol. 83, p. 423
Milone A., Barbuy B., 1994, A&AS 108, 449
Nemec J.M., Nemec A.F.L., Lutz T.E., 1994, AJ 108, 222
Plez B., 1992, A&AS 94, 527
Plez B., Brett J.M., Nordlund Å., 1992, A&A 256, 551
Ridgway S.T., Joyce R.R., White N.M., 1980, ApJ 235, 126
Turon C., 1995, Le diagramme HR des étoile proches. In: M. Froeschlé, F. Mignard (eds) Atelier du GDR 051, De l'utilisation des données Hipparcos, p. 123
Tuchman Y., Sack N., Barkat Z., 1979, ApJ 234, 217
Tuchman Y., Lebre A., Mennessier M-O., Yarri A., 1993, A&A 271, 501
Van Altena W.F., Truen-Liang Lee J., Hoffleit D., 1991, New General Catalogue of Trigonometric Stellar Parallaxes, Yale Univ. Obs., New Haven
Vassiliadis E., Wood P.R., 1993, ApJ 413, 641
Whitelock P., Menzies J., Feast M., Marang F., Carter B., Roberts G., Catchpole R., Chapman J., 1994, MNRAS 267, 711
Wing R.F., 1967a. In: M. Hack (eds.) Colloquium on late-type stars. Osservatorio Astronomico di Trieste, p. 231
Wing R.F., 1967b. In: M. Hack (eds.) Colloquium on late-type stars. Osservatorio Astronomico di Trieste, p. 205
Wing R.F., Yorka S.B., 1977, MNRAS 178, 383
Wood P.R., 1989, Pulsation and evolution of Mira variables. In: M-O. Mennessier and A. Omont (eds.) From Miras to planetary nebulae, Editions Frontières, p. 67

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.