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Oxygen-rich Mira variables: near-infrared luminosity calibrations*

Populations and period–luminosity relations

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Abstract. HIPPARCOS astrometric and kinematical data of oxygen-rich Mira variables are used to calibrate absolute near-infrared magnitudes and kinematic parameters. Two sets of near-infrared magnitudes compiled from different authors are used: broad-band K and narrow-band photometric measurements at 1.04 μm (104 filter). Three distinct classes of stars with different kinematics and scale height have been identified. The two most significant groups present characteristics close to the ones usually assigned to extended/thick disk–halo population and old disk population respectively, and thus they might differ by their metallicity abundance. They exhibit different period distributions, as expected if these two groups actually correspond to populations of distinct initial masses, ages and metallicities. Two parallel period–luminosity relations are found in K as well as in 104, one for each significant population. The shift between these relations is interpreted as the consequence of the effects of metallicity abundance on the luminosity.

Key words: stars: distances – stars: fundamental parameters – stars: AGB, post-AGB – Galaxy: stellar content

1. Introduction

Mira variables, due to their intrinsic brightness and large range of their ages, mark a unique stage in stellar evolution of intermediate-mass stars and thus are important in the study of stellar populations in our Galaxy. Knowledge of their distances is crucial to understand the Galactic structure evolution as well as the pulsational properties of these stars. The existence of infrared and bolometric period–luminosity (PL) relations in the Large Magellanic Cloud (LMC) for Mira variables (see, e.g., Feast et al. 1989) has allowed us to estimate Galactic distances for a large number of Miras (Jura & Kleimann 1992; Jura et al. 1993; Alvarez & Mennessier 1997). But such works have been limited by the (unavoidable untill recently) assumption on the choice of the zero point for the Galactic Mira PL relation. Now, the release of HIPPARCOS data enables one to proficiently investigate this particular point.

The results presented in this paper constitute the application of the LM (Luri, Mennessier et al. 1996a; hereafter Paper I) method to HIPPARCOS data concerning oxygen-rich Miras. This method is based on a maximum-likelihood estimation using apparent magnitudes, trigonometrical parallaxes, proper motions and radial velocities. It has been applied to two different samples of about one hundred oxygen-rich Miras for which two sets of near-infrared (K and 104) magnitudes at maximum have been compiled from different authors. These apparent magnitudes complement the kinematical data: the trigonometric parallaxes and proper motions are obtained from the recently available HIPPARCOS Catalogue (ESA 1997) and the radial velocities from the HIPPARCOS Input Catalogue (Turon et al. 1992).

A preliminary approach to the fundamental problem of absolute magnitudes and distances determinations was made by Luri et al. (1996b) using HIPPARCOS Input Catalogue kinematics data and visual magnitudes. Infrared data are maybe more suitable to study the very cool stars as they emit most of their energy in the infrared. At least in K band, these measurements are less sensitive than visual magnitudes to interstellar and circumstellar extinction. The effect of molecular absorption, which considerably varies in visual region over a cycle, is also weaker in K or 104. Furthermore, the existence of period–luminosity relations is well attested in infrared bands. All these properties contribute to the interest of applying the LM method to near-infrared data.

2. The samples and data

In this paper, we focus on oxygen-rich Miras with available data in HIPPARCOS Catalogue: they constitute a first sample of nearly 200 objects. Only part of them have been observed in

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* Based on data from the HIPPARCOS astrometry satellite

near-infrared. As a maximum-likelihood method gives statistical results, the need for a sufficiently large working sample is therefore critical. Thus, we decided to also include oxygen-rich semi-regular (SR) variables in order to produce more reliable estimations. The SR variables are very similar to the Miras: they are arbitrarily discriminated from Miras according to their smaller visual amplitude, but, as observed in the LMC (Hughes et al. 1990), their absolute magnitude distributions should be similar. We have checked a posteriori that the oxygen-rich SR and the M–Miras of our sample actually exhibit similar kinematics and luminosities. The so-defined sample is thus kinematically homogeneous so that the LM method could be used with benefit. SR variables will be studied apart in a forthcoming paper. The trigonometric parallaxes and proper motions of the initial sample are obtained from the HIPPARCOS Catalogue (ESA 1997). They are complemented with radial velocities (HIPPARCOS Input Catalogue, Turon et al. 1992) and with:

1. **apparent K magnitudes** at maximum luminosity compiled from different sets of K–band observations available in the literature: Catchpole et al. (1979) presented a total set of 2883 JHKL measurements of 223 Mira-type variables and 404 late-type stars of various types; Fouqué et al. (1992) published JHKLM photometry of 516 sources pertaining to the IRAS Point Source Catalogue; Whitelock et al. (1994) gave over 1500 JHKL photometry observations for 61 Miras; Kerschbaum & Hron (1994) and Kerschbaum (1995) presented JHKL'M observations of respectively 200 and 44 SR variables.
2. **apparent 104 magnitudes** at maximum luminosity. The 104 filter forms part of a five-colour narrow-band photometric system used by Lockwood (1972). He observed 281 M– and S–type Mira variables and 11 SR stars for a total of nearly 1800 sets of measurements. The five-colour photometric system is based on Wing's 27 colours system (Wing 1967). The peak wavelength of the 104 filter is 10351 Å, and the half-power bandwidth is 125 Å. This narrow-band filter matches a region relatively free of molecular absorption (Wing 1967; Alvarez & Plez 1997) and hence can be considered as a reliable measurement of "continuum". Furthermore, the distances that can be derived from apparent 104 magnitudes are in good agreement with those obtained using apparent K magnitudes (Alvarez & Mennessier 1997). The 104 filter can be regarded as meaningful as K band in the study of these late-type stars. From Lockwood's sample, only stars with at least one observation in the phase range 0.8–0.2 (i.e. near maximum luminosity) have been kept before determining the brightest 104 value.

The two final samples are coincidentally both composed of 103 Mira variables, plus 129 SR and 8 SR for the K and 104 sample respectively. Seventy variables (64 Miras and 6 SR) belong to both of them.

3. The method

The reader is referred to Paper I for a thorough description of the LM method. We outline here its most important features. This method, based on the maximum-likelihood principle, allows us to simultaneously calibrate the luminosity and determine the mean kinematic characteristics and spatial distribution of a given sample. This sample is specifically modeled with appropriate distribution functions corresponding to the absolutes magnitudes, kinematics and spatial distribution. Sampling effects, the galactic differential rotation and observational errors are rigorously taken into account by including appropriate functions in the density law describing the sample. The effects of the observational errors in apparent magnitude are neglected, and only the errors in trigonometrical parallax, proper motions and radial velocity are included in the density law. The method is able to use inhomogeneous samples, i.e. samples composed of a mixture of groups of stars with different luminosity, kinematics or spatial distribution. In this case the method identifies and separates the groups. Moreover, the LM method assigns each star to a group and estimates its most probable distance.

In view to model each group of stars, the following distribution functions have been adopted:

1. **Distribution of absolute infrared magnitudes:** a gaussian law with mean M_0 and standard deviation σ_M
2. **Velocity distribution:** a Schwarzschild ellipsoid with means (U_0, V_0, W_0) and dispersions $(\sigma_U, \sigma_V, \sigma_W)$
3. **Spatial distribution:** an exponential disc with scale height Z_0

These parameters are determined by the LM method at the same time as the relative proportion of each group.

4. Populations separation

4.1. Absorption correction in 104

The interstellar absorption is taken into account by the LM method in the determination of the parameters. Fluks et al. (1994) have tabulated an extended mean extinction law based on the observed mean extinction law of Savage & Mathis (1979) and on the theoretical extinction law of Steenman & Thé (1989, 1991). From the tabulated $a(\lambda)/E_{B-V}$ values, it appears that the extinction in 104 is smaller than in V by a factor 0.37, which is non-negligible.

The absorption correction in 104 is done by using a detailed model of visual interstellar absorption, based on the scheme of Arenou et al. (1992), scaled by the factor 0.37. A null absorption correction is assumed for the K magnitudes. As quoted by Allen (1973), absorption is less pronounced in K than in V by at least a factor ten and thus it should be negligible. The validity of this particular point will be checked later.

4.2. Number of groups and mean parameters

Wilks test indicates that the three group solution is the optimal one for both samples. Tables 1 and 2 give the maximum-likelihood estimates of the parameters for the K and the 104 sample respectively. In these tables, the estimates of the parameters are given in the columns marked θ and the corresponding errors are given in the columns marked σ. These errors were

Table 1. Model parameters using $m_{\rm K}$ (232 variables including 103 Miras)

		group 1		group 2		group 3	
		θ	σ	θ	σ	θ	σ
M_0	(mag)	-6.3	0.7	-6.1	1.6	-6.7	0.9
σ_M	(mag)	1.0	0.4	0.4	0.4	0.8	0.5
U_0	(km.s^{-1})	-11	6	-53	17	-33	40
σ_U	(km.s^{-1})	37	8	1	7	93	34
V_0	(km.s^{-1})	-23	6	-57	74	-93	53
σ_V	(km.s^{-1})	22	4	15	30	75	24
W_0	(km.s^{-1})	-12	4	-33	10	-2	33
σ_W	(km.s^{-1})	20	5	3	4	58	31
Z_0	(pc)	260	40	370	180	820	240
%		81	7	2	1	17	7

Table 2. Model parameters using m_{104} (111 variables including 103 Miras).

		group 1		group 2		group 3	
		θ	σ	θ	σ	θ	σ
M_0	(mag)	-5.3	0.4	-5.5	1.5	-5.6	0.9
σ_M	(mag)	0.9	0.2	1.0	0.9	1.0	0.5
U_0	(km.s^{-1})	-14	8	-51	12	-32	40
σ_U	(km.s^{-1})	45	13	2	2	117	45
V_0	(km.s^{-1})	-21	7	-41	9	-123	42
σ_V	(km.s^{-1})	25	7	5	2	41	31
W_0	(km.s^{-1})	-9	4	-34	19	-8	37
σ_W	(km.s^{-1})	20	9	14	4	75	37
Z_0	(pc)	400	130	160	80	2630	1020
%		73	8	6	3	21	8

calculated using Monte-Carlo simulations: simulated samples were generated and LM estimations were performed with them. The dispersion of these estimates was taken as the error on the results.

The two sets of kinematic parameters are in good agreement given the estimation errors. It is extremely satisfactory to obtain such a good agreement despite the uncertainties inherent to any statistical method, and despite the fact that the majority of both samples differ. Among the 70 common variables, only 8 are classified in discrepant groups.

Two significant populations are well separated. Group 1, which is the main one (about 75% of the sample), has the kinematics of late disk stars. The scale height is characteristic of the old disk population (it is perhaps slightly too large for the 104 sample). This group can be interpreted as the standard population which has a exponential scale height of $\sim$ 300 pc (Jura & Kleinmann 1992). Group 3 (about 20% of the samples) has a larger velocity ellipsoid. The scale height is much more important. The very large scale height in Table 2 is an artifact of the method: it only means a spherical spatial distribution. The large velocity ellipsoid and the important scale height characterizes a population older than the group 1. They might belong to the extended/thick (E/T) disk or they might be halo stars.

The mean period of the Mira variables belonging to group 1 is 321 d for the K sample and 308 d for the 104 sample. It is respectively 217 d and 216 d for the Miras of group 3. Both distributions are overlapping. The existence of different period distributions was already attested by Jura & Kleinmann (1992) and certainly reflects the different evolutionary paths followed by two populations of distinct initial masses, ages and metallicities.

Group 2 is a very small group with very low velocity dispersion. They might form a sub-population of younger stars. The small number of stars prevents further interpretation.

The present results are in good agreement with those obtained by Luri et al. (1996b) for a sample of 90 M–Mira variables using apparent *visual* magnitudes and HIPPARCOS Input Catalogue data (Turon et al. 1992). In particular, the three present groups were already attested. This confirms the confidence that we can have in the results, since the data differ by the samples size, the apparent magnitudes, the source and the accuracy of the proper motions and the introduction of the parallaxes.

Comparaison has also been performed with the results of Mennessier et al. (1997a, hereafter Paper II; 1997c) who have applied the LM method to the total sample of Long Period Variables (LPVs), i.e. Mira, SR and Irregular variables, of M, S and C type (nearly 900 stars), using apparent visual magnitudes and HIPPARCOS data (ESA 1997). As this total sample is very large and its observational selection criteria (Mennessier & Baglin 1988) are well defined, the kinematic parameters and the population separation obtained in Paper II should be considered as the most reliable among all the applications of the LM method to sub-samples of LPVs. The results of Paper II show a separation into several groups. Indeed, due to the larger number of stars, the partition into the different groups is more accurate than ours and several populations can be defined: they represent the gradual transition between the younger disk population and the stars clearly belonging to the halo. A specific look at the oxygen-rich Miras confirms what we find in the present work: they mainly (79%) belong to the groups that correspond to the old disk population, while a non-negligible fraction (12%) are found in the groups that might be assimilated to the E/T disk and the halo. Some M–Miras (9%) belong to a younger disk population.

5. Comparison of distance estimates

Once a star is assigned to a group, the LM method enables us, via the distance marginal density law, to estimate the most probable value of the distance and its error. For each star a distance $r_{\rm K}$ and/or a distance r_{104} is therefore proposed. The distance estimates using the apparent V magnitudes (Paper II), $r_{\rm V}$, are compared to the distances derived from the K and 104 magnitudes in Fig(s). 1 and 2 respectively. The stars are denoted by symbols indicating the population to which they belong *as assigned by the classification of Paper II*, i.e. younger disk population (asterisks), old disk population (open circles) or E/T disk and the halo population (filled circles).

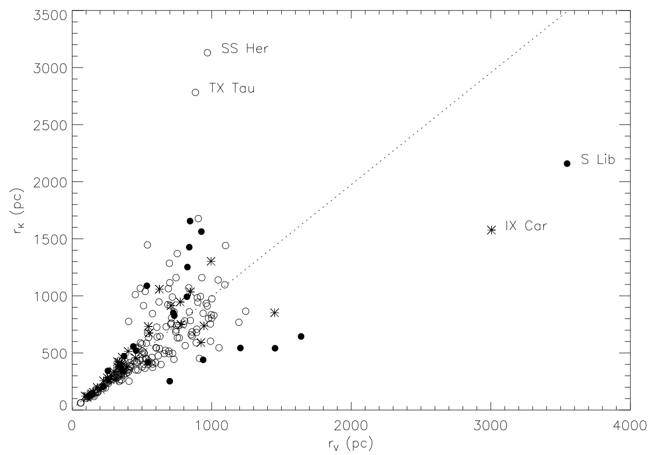

Fig. 1. Comparison of the distance estimates using the apparent K magnitudes (this work) and those using the apparent V magnitudes (Mennessier et al. 1997a,c). Asterisks represent LPVs belonging to the younger disk population, open circles to the old disk population and filled circles to the E/T disk or halo population, as determined by the classification of Mennessier et al. (1997a,c). The dotted line is the regression line

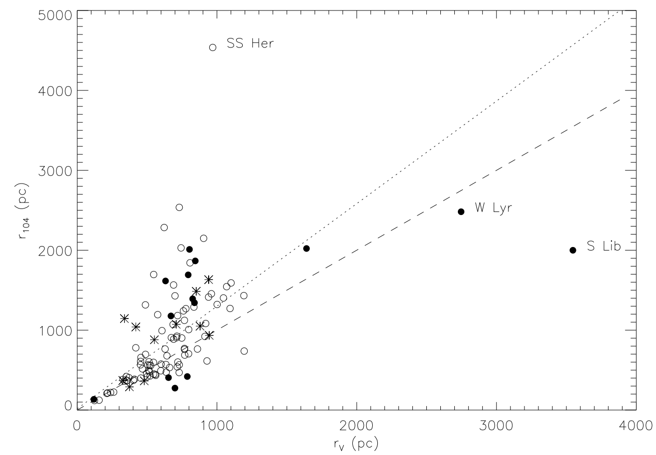

Fig. 2. Comparison of the distance estimates using the apparent 104 magnitudes (this work) and those using the apparent V magnitudes (Mennessier et al. 1997a,c). Same symbols as Fig. 1. Dotted and dashed lines are the regression and one-to-one lines respectively

The distances r_K are in good agreement with the distances r_V, considering the unavoidable uncertainties which result from the statistical character of the estimating method and increase with distance. A least-squares linear fit gives $r_K \approx 0.98 r_V$. The regression line is indicated in Fig. 1. It is worth remarking that no systematic discrepancy appears between the two sets of distances. This confirms that the extinction in K is very small. The outlying stars are indicated with their name. Assignation to different populations in V and in K explains these discrepancies. Indeed, the group assignation is only a statistical result and some inconsistencies remain.

For the 104 distances, a least-squares linear fit gives $r_{104} \approx 1.28 r_V$. As in K and for the same reason, there are some outlying stars. The systematic discrepancy might be due to sampling effects generating a bias. Indeed, due to the small number of objects, the sample of 104 observations is probably not well representative of the HIPPARCOS sampling function adopted in our calculations. As a consequence, the 104 distances and magnitudes are probably less reliable than the K ones. Nevertheless, it is remarkable that the noticeable results from K presented in Sect. 4 (separation into populations of different kinematics and period distribution) and those of Sect. 6 (existence of two nearly parallel period–luminosity relations) still hold from 104.

6. Mira period–luminosity relations

6.1. Period–luminosity relations and populations

The individual absolute magnitudes of Miras can also be obtained with the LM method. They are plotted against the logarithm of the periods in Fig(s). 3 and 4, which correspond to the K and 104 samples respectively. Periods were taken from the General Catalogue of Variable Stars (Kholopov 1985, 1987) or from Mennessier et al. (1997b). The three groups that we defined in the present work are distinguished by different symbols. For the two most significant groups (1 and 3), least-square linear fits are obtained. The different equations of the regression lines for our HIPPARCOS samples are:

1. In K band:
   (a) Group 1 (85 Miras)
   $$M_K = 0.976 - 3.41 \log P, \qquad \sigma = 0.72 \qquad (1)$$
   (b) Group 3 (16 Miras)
   $$M_K = -0.129 - 3.18 \log P, \qquad \sigma = 0.52 \qquad (2)$$
2. In 104 filter:
   (a) Group 1 (76 Miras)
   $$M_{104} = -0.755 - 2.19 \log P, \qquad \sigma = 0.54 \qquad (3)$$
   (b) Group 3 (19 Miras)
   $$M_{104} = -0.804 - 2.52 \log P, \qquad \sigma = 0.67 \qquad (4)$$

The period–luminosity relations determined for groups 1 and 3, in K as well as in 104, are remarkably parallel, despite the large scatter about the regression lines. The different period distributions of the groups do not prevent from obtaining similar slopes. It is worth recalling that periods do not appear as input data in the application of the LM method: the determination of absolute magnitudes is totally period-independent. These results are thus very satisfactory, since oxygen-rich Miras in the Large Magellanic Cloud are known to obey a PL relation in the K band (Feast et al. 1989) with the same slope as ours. As far as we know, this is the first time that the existence of a PL relation in 104 is demonstrated. This result confirms that 104 is as suitable as K to study red variables.

The PL fits presented in Eq. (1-4) are the relations *of our samples*. The PL relations of the whole oxygen-rich Miras population are expected to be less luminous due to the effects of the Malmquist bias (Malmquist 1936).

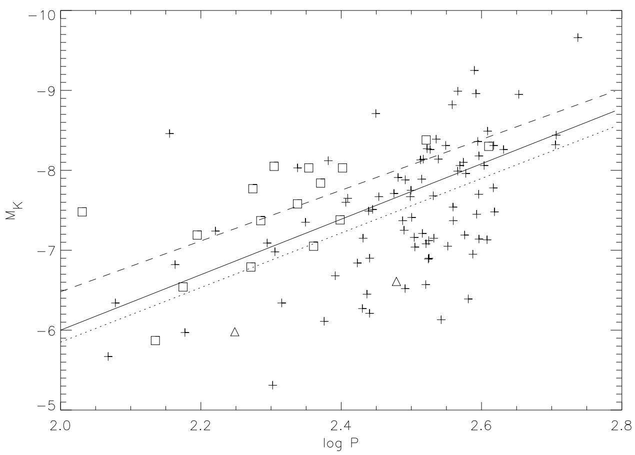

Fig. 3. Period–luminosity relations in K band. Crosses represent Miras belonging to group 1, triangles to group 2 and squares to group 3. Dotted line and dashed line are the PL fit relations for group 1 and 3 respectively. Solid line is the PL relation determined by van Leeuwen et al. (1997)

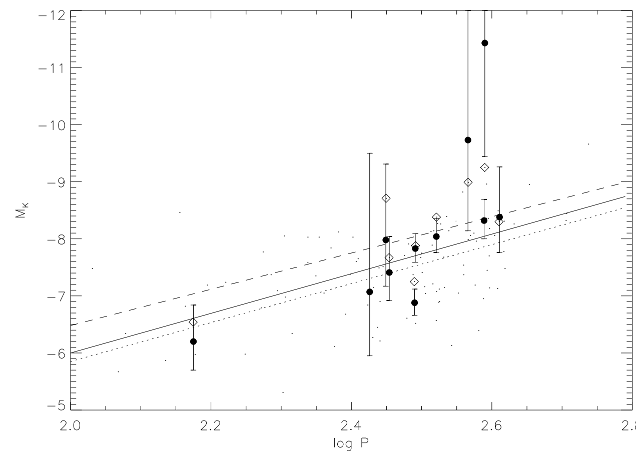

Fig. 5. Period–luminosity relations in K band. The lines have the same meaning as in Fig. 3. Filled circles are the Miras used by van Leeuwen et al. (1997) to calibrate the zero-point of the Galactic PL relation and diamonds are their $M_{\rm K}$ value as determined by the LM method when available. The other sample stars are represented by dots

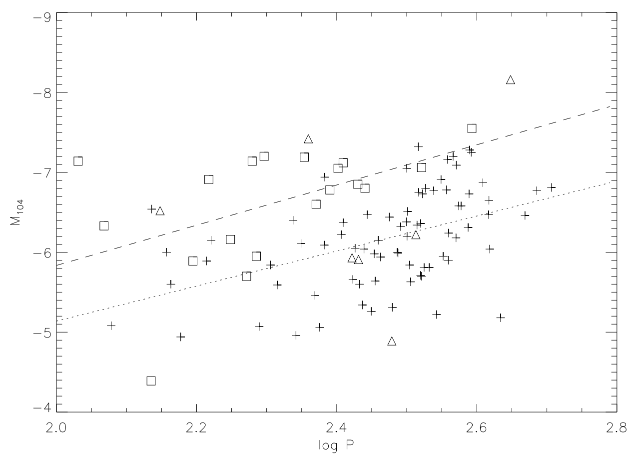

Fig. 4. Period–luminosity relations in 104 filter. Same symbols as Fig. 3

6.2. Effects of metallicity on the period–luminosity relation

It has been discussed for a long time as to whether metallicity effects in Miras might generate different PL relations. Wood (1990), extrapolating results from pulsating theory, argues that local Miras are intrinsically fainter than in the LMC, because of the different metal abundance: Galactic Miras might be about 0.25 mag fainter in K than those in the LMC. Whitelock et al. (1994) showed on the contrary that Miras in the LMC, the Galactic globular clusters and the solar neighbourhood might obey a single PL relation.

Recently, van Leeuwen et al. (1997) have calibrated the zero-point of the $M_{\rm K}$–P relation for Galactic oxygen-rich Miras by using HIPPARCOS parallaxes and adopting the slope of the LMC relation. They obtained:

$$M_{\rm K} = 0.94 - 3.47 \log P \quad (5)$$

This relation is shown in Fig. 3. Its slope is in very good agreement with ours. This is a very remarkable result: we find that the slopes of the Galactic PL relations in K are the same as the LMC one.

From the agreement between the distance modulus of the LMC derived from their zero-point calibration of the PL relation, and the current Cepheid distance modulus (Feast 1995), Van Leeuwen et al. conclude that it is very unlikely that Miras could be affected by some metallicity effects. Fig. 5 is basically the same as Fig. 3, with the addition of the location of the 11 Miras used by van Leeuwen et al. for calibrating the zero-point. They are represented by filled circles; the 1σ error bars are shown. Among these 11 Miras, 6 belong to our group 1, and 3 to group 3 (the two others do not appear in our K sample). Diamonds indicate their absolute K magnitude as determined by the LM method. The other stars of the sample are represented by dots. The lines of Fig. 3 are reported. We may conclude from Fig. 5 that:

1. the scatter of the Miras used by van Leeuwen et al. around their PL relation is comparable to ours
2. since these authors could not separate distinct populations, they found a single PL relation which naturally lies between our two fits, and closer to the relation of the predominant population which is group 1.

By this, we stress the necessity to consider large sample of Galactic oxygen-rich Mira variables and to separate the different populations with the help of a metallicity estimator or with a method such as LM when deriving PL relations for the Galaxy.

The results of the present work tend to demonstrate that Galactic Miras follow different PL relations, both in K and in 104. The slopes are the same. Only the zero points differ by about 0.5 mag in K and 0.8 mag in 104 according to the two distinct populations that we have separated. This shift can be interpreted as a metallicity and mass effect.

As mentionned above, according to Wood (1990), changing Z from $Z_\odot$ to $Z_\odot/4$ will shift $M_{\rm K}$ by 0.25 mag. Assuming that the magnitude is related to the metallicity by a power law, a shift by 0.5 mag in K corresponds to a metallicity of $Z_\odot/16$ for the Miras of the E/T disk–halo population, which value is not striking.

7. Conclusions

In this work we have made use of a powerful tool – the maximum-likelihood LM method – applied to HIPPARCOS data and near-infrared apparent magnitudes for a large sample of Mira variables. In K as well as in 104, we separate three populations which exhibit different kinematics and exponential scale heights. The two most significant populations can be interpreted as the old disk population and the extended/thick disk–halo population respectively. So they probably differ by their metallicities. They also exhibit clearly distinct period distribution: this important result corroborates that the two populations are certainly composed of stars of different masses, age and metallicity abundance.

The LM method enables us to derive individual distances. They were compared to the ones derived from visual magnitudes (Mennessier et al. 1997a,c). Distances $r_{\rm K}$ are in good agreement with those obtained with visual data. There is a discrepancy found between the distances r_{104} and the distances $r_{\rm V}$, which might be due to sampling effects.

Two parallel period–luminosity fit lines are obtained in K as well as in 104 for the Mira variables samples. The slope in K is very similar to the one observed in the LMC (Feast et al. 1989). The Galactic PL relation calibrated by van Leeuwen et al. (1997) lies between our two fits. The shift between our PL relations is probably due to metallicity and mass effects. We stress the necessity to take into account a possible distinction between populations when deriving PL relations for the Galaxy.

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