

Absolute magnitudes and kinematics of oxygen Mira variables

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Abstract. A new maximum likelihood method, using apparent magnitudes, proper motions and radial velocities, has been applied to a sample of 90 Mira stars extracted from the HIPPARCOS Input Catalogue (INCA) to determine absolute magnitudes and kinematics. Using this new method three different groups of Mira stars have been identified in the sample, with different luminosities, kinematics and scale height. Two of them are well determined and are identified respectively with the old disk population and the extended thick disk-halo population. The third one is too small and peculiar and its identification has to be left for further studies.

Using these results the stars of the sample are classified into the groups and their distances are estimated. These distances are compared with independent determinations obtained from K-band and near-infrared narrow band photometry.

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

1. Introduction

The results presented in this paper constitute one of the first test applications to real data of a new Maximum Likelihood (hereafter ML) method developed to optimize the exploitation of the long awaited HIPPARCOS results – see Sect. 3, Luri (1995) and Luri et al. (1996) –. The method estimates absolute magnitude, kinematics and spatial distribution of a sample of stars using apparent magnitudes, proper motions and radial velocities, so it is specially useful for samples of distant stars, like Mira variables, for which very few trigonometric parallaxes are available.

The absolute magnitude of Mira variables has already been studied using statistical parallaxes – Clayton and Feast (1969) – and ML methods – Foy et al. (1975) – but there are several reasons to review the problem:

1. These results are rather old. They can be improved using better proper motions and radial velocities available nowadays.
2. Our ML method presents several improvements with respect to those used in previous determinations – see Sect. 3 –, the main ones being a better modelisation of the sample, a rigorous treatment of the observational errors and the use of a detailed model of interstellar absorption.
3. The method is also able to identify and separate physically distinct groups of stars in the sample. In this way, the presence of different stellar populations in the sample can be detected and a calibration can be provided for each one of them. If this detection is not performed, as in previous works, the resulting calibration can be severely biased.
4. A better knowledge of oxygen Mira variables can contribute to the study of several important astrophysical problems. Indeed, it is well known that they come from main-sequence stars covering a large range of initial masses, so they can have very different ages and belong to different galactic populations. Mira stars can lose more than half of their initial mass, so their spatial distribution can trace out both the distribution of stars in the Milky Way and the places where the interstellar medium is being enriched in heavy elements. Moreover, a precise luminosity calibration can greatly help to disentangle the difficult and unsolved problem of the main pulsation mode of Mira variables.

Our teams will continue to study the absolute magnitudes and kinematics of Mira variables in next years using the HIPPARCOS mission data, the results presented in this paper are the first contribution to this field.

2. The sample

The working sample has been selected from the HIPPARCOS Input Catalogue (INCA) – see Turon et al. (1992) –. All oxygen Mira variables with INCA proper motions and radial velocities were selected, forming a sample of 90 stars. Other radial velocities (from radio observations) that would have allowed us to form a larger sample were available, but to keep the homogeneity of these parameters they have not been used – the radial

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velocity radio observations seem to show a systematic difference of about 4Km s^{-1} with respect to the ones measured from spectra, Barbier et al. (1988) –.

The INCA data were completed with the mean apparent magnitudes at the maximum and at the minimum given by Boughaleb (1994). These apparent magnitudes improve those given in INCA because they are the mean of 75 years of AAVSO observations instead of being based on statistical corrections applied to GCVS magnitudes – which correspond to the brightest and the faintest observed luminosities. See Turon et al (1992) –.

The sample was tested for representativeness of the population of oxygen Mira stars using the General Catalogue of Variable Stars – Kholopov (1985) –. The respective distributions of periods, proper motions and radial velocities show no significative differences, indicating that the results derived in this paper can be extended in broad terms – not in detail, due to the small size of the sample – to the entire population.

3. The method

The results presented in this paper were obtained using a new statistical parallax method, based on the ML principle, that allows us to simultaneously calibrate the luminosity and determine the kinematic characteristics and spatial distribution of a given sample. This method, especially useful for samples including distant stars, has been developed for the exploitation of the HIPPARCOS data and presents several improvements with respect to the previous ones – Rigal (1958), Jung (1970) and Heck (1975) –. A complete description can be found in Luri (1995) and Luri et al. (1996), but its main characteristics are:

- It allows a specific modelisation of the sample. Appropriate distribution functions for the absolute magnitudes, kinematics and spatial distribution can be chosen for a given sample and then introduced in the method.
- The effects of the selection of the sample are rigorously taken into account. The selection criteria are modeled using a function (the selection function \mathcal{S}) and then included in the density law describing the sample, so the estimations are unbiased – see Luri et al. (1993) and for more details Luri (1995) –.
- The observational errors can be treated rigorously. They are modeled using error distributions, which are then included in the density law describing the sample, taking into account the individual errors of each star. We use gaussian error distributions, but the method is not limited to them; other distributions could be used if necessary. In the present case, however, the effects of the observational errors in apparent magnitude are not included, as discussed below, and only the errors in proper motions and radial velocity are included in the density law of the sample.
- The galactic differential rotation is modeled using the Oort-Lindblad rotation model at first order and then included in the density law describing the sample.
- A detailed model of interstellar absorption is used. The model divides the sky in 199 regions and gives a mean law

for each region – Arenou et al. (1992) –. These mean laws are included in the density law describing the sample, so the absorption is intrinsically taken into account.

- 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.

In addition to these improved characteristics, a computer implementation of the method, relying only on numerical procedures, has been developed. In this way analytical approximations – which were necessary in previous methods – are avoided and a greater flexibility – facilitating the use of varied density laws – is achieved.

As stated above, the implementation of the method used for the oxygen Mira stars does not directly include the errors in apparent magnitude in the density law describing the sample. This is a deliberate choice related to the characteristics of the interstellar absorption model. Indeed, the model gives a *mean* law for each sector of the sky, so the real absorption will present variations or “fluctuations” around it. These fluctuations can be modeled, as the Arenou et al. (1992) model provides an estimation of their value, and included in the density law at the same time as the observational errors in apparent magnitude, but this double inclusion makes the maximization of the likelihood very cumbersome. An alternative procedure, based on the use of simulated samples, has been chosen. A first ML estimation not taking into account either the errors in apparent magnitude or the fluctuations of the interstellar absorption is performed. Using the results so obtained, the possible biases introduced for these exclusions are estimated using simulated samples – see Luri et al. (1996) –. In the case of oxygen Mira variables these biases have been found to be much smaller than the estimation errors and have been neglected.

To modelize the physics of the group(s) of stars composing our sample of oxygen Mira variables, several distribution functions have been chosen:

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

As described above, these functions depend on several parameters and the physics of each group is described by a set of values,

$$(M_{0i}, \sigma_{M_i}, U_{0i}, V_{0i}, W_{0i}, \sigma_{U_i}, \sigma_{V_i}, \sigma_{W_i}, Z_{0i}). \quad (1)$$

These parameters are determined by ML at the same time as the relative abundance of each group w_i .

There are still other parameters to be determined by ML: those contained in the Selection function. This function has been constructed from the criteria used to select our sample:

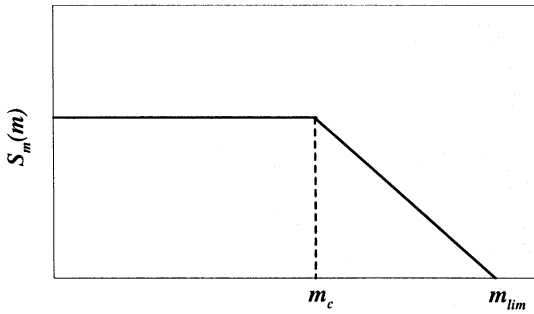


Fig. 1. distribution function describing the probability of selecting a star with apparent magnitude m

1. Only variables with $\Delta m > 2.5^m$ are considered Miras. Otherwise they are considered Semiregulars and not included in our sample.
2. No Mira variable with amplitudes greater than 7^m is observed, so $\Delta m \leq 7^m$.
3. The sample has been extracted from the INCA so it shares its observational selection criteria – see Mennessier and Baglin (1988) –:
 - A limit in magnitude of $H_{lim} = 12.4^m$, corresponding for visible wavelengths to $m_{lim} = 12.5^m \pm 0.5^m$ for the $(B - V)$ range of Mira stars, $(B - V) \simeq 1.5^m$ – see Grenon (1988).
 - Only the stars that could be observed by HIPPARCOS during at least the 80% of their variation cycle were included in the catalogue. This condition can be expressed using the apparent magnitudes at the maximum and at the minimum as:

$$m_{min} < 15.62 - 0.25m_{max} \quad (2)$$
4. Only stars with INCA proper motions and radial velocities have been selected. This selection does not affect the distributions of proper motions or radial velocities themselves, as it does not depend on the values of these quantities, but has some effect in the distribution of apparent magnitudes. Indeed, the selection of samples for measures of radial velocities and/or proper motions tends to favour the bright ones, so the choice of stars with measures of these quantities introduces a selection bias in apparent magnitudes.

The combination of the first three criteria produces a selection in apparent magnitudes that is described by the distribution function depicted in Fig. 1; the quantities m_c and m_{lim} are determined by the criteria but being different when using the apparent magnitudes at the maximum and when using the apparent magnitudes at the minimum.

The fourth criterion does not produce any selection in proper motions or in radial velocities, because the values of these quantities do not play a role in the choice, only its presence or absence. It produces, however, a selection in apparent magnitude. The brighter stars are more easily selected as candidates for measurements of proper motions and/or radial velocities, so the fourth criterion tends to favour bright apparent magnitudes. This selection effect cannot be modeled a priori due to varied origins of the measurements and the lack of information about the se-

lection processes, but it can be modeled *on the fly*. The function shown in Fig. 1 does already describe a selection favouring bright magnitudes and it can be generalized by treating the quantity m_c as a parameter to be determined by ML, instead of a fixed value. In this way the global bias towards bright apparent magnitudes caused by the four criteria is modeled when the physical parameters are estimated. This modelization is simple and it could be improved by generalizing the shape of the function – introducing new parameters – but it is enough for a preliminary study with a limited sample, like the one presented in this paper. However, to refine this model, a value of m_c is determined for each of the groups forming the sample instead of a single value for all the stars.

In conclusion, the selection function used to describe the selection of our sample depends only on the apparent magnitude and has the shape given in Fig. 1, defined by two parameters: m_c , to be determined by ML for each group, and m_{lim} , known beforehand. Their value depends on the apparent magnitude used; the value of m_{lim} is 10.5^m when using the apparent magnitudes at the maximum and 13.9^m when using the apparent magnitudes at the minimum. Note that this selection function can also be applied to the treatment of the final HIPPARCOS data.

Finally, the set of parameters to be determined by ML for each group can be written as

$$\theta_i = (M_{0i}, \sigma_{M_i}, U_{0i}, V_{0i}, W_{0i}, \sigma_{U_i}, \sigma_{V_i}, \sigma_{W_i}, Z_{0i}, m_{ci}, w_i). \quad (3)$$

4. Results

The first set of results is presented in Tables 1 – corresponding to the results using the apparent magnitude at the maximum – and 2 – corresponding to the results using the apparent magnitude at the minimum –.

In these tables the ML estimates of the sample parameters are given in the columns marked θ_{MV} and the corresponding errors are given in the columns marked σ . These errors were calculated using Monte-Carlo simulations: simulated samples of the same size as ours were generated using each set of results (20 for the maximum and 20 for the minimum) and ML estimations were performed with them. The dispersion of these estimates was taken as the error of the results for our sample.

In both cases the number of groups of the fit was determined using a likelihood test, the Wilks test – see Soubiran et al. (1990) –. This test indicated the presence of at least three groups and, given the reduced size of the sample, no more than three could be used.

Although these two sets of results are in general agreement, some discrepancies remain. The most significant are the relative abundances of the three groups and, correlated with them, the asymmetrical drift for group 3. Due to these discrepancies a more elaborate model of the sample was attempted, including a period-absolute V magnitude relation for each group. In this case the three groups were found again and the results from the maximum and from the minimum were much more coherent – see Luri (1995) –. However, the results also showed that there

Table 1. Results using m_{\max}

	group 1		group 2		group 3	
	θ_{MV}	σ	θ_{MV}	σ	θ_{MV}	σ
M_0 (m)	0.4	0.6	-1.8	0.9	-2.5	0.4
σ_M (m)	1.0	0.2	1.0	0.4	0.1	0.4
U_0 (Km s^{-1})	-16	7	-49	10	-69	28
σ_U (Km s^{-1})	44	5	12	6	85	25
V_0 (Km s^{-1})	-33	6	-37	5	-139	55
σ_V (Km s^{-1})	39	6	0	2	83	29
W_0 (Km s^{-1})	-5	6	-22	12	-9	32
σ_W (Km s^{-1})	23	7	12	8	205	39
Z_0 (pc)	329	81	47	18	390	180
m_c (m)	6	1	5	2	3	2
%	75	8	9	2	16	7

Table 2. Results using m_{\min}

	group 1		group 2		group 3	
	θ_{MV}	σ	θ_{MV}	σ	θ_{MV}	σ
M_0 (m)	6.3	0.3	2.4	0.8	0.1	0.8
σ_M (m)	1.4	0.1	0.7	0.4	0.1	0.6
U_0 (Km s^{-1})	-19	9	-51	8	-65	70
σ_U (Km s^{-1})	46	5	12	6	86	60
V_0 (Km s^{-1})	-38	8	-39	4	-220	60
σ_V (Km s^{-1})	41	3	0	5	93	50
W_0 (Km s^{-1})	-7	3	-23	9	-4	160
σ_W (Km s^{-1})	31	2	16	7	300	130
Z_0 (pc)	900	800	51	25	550	260
m_c (m)	12	0.4	9	2	12	2
%	84	3	10	2	6	3

was no clear correlation between period and absolute V magnitude inside each group. Then, as the role of the period was only to contribute to a clear separation of the groups, we decided to keep it without introducing the period-absolute V magnitude relation. A distribution of periods was then added in the modeling of the groups and was assumed to be normal in $\log(P)$ after examination of the sample data. Two parameters of the distribution were determined for each group, its mean $\overline{\log(P)}$ and its dispersion $\sigma_{\log(P)}$. The obtained results are presented in Tables 3 and 4.

The two sets of results using the period are in very good agreement and also close to those shown in Table 1. Moreover, as discussed below (Sect. 6), the classification of the stars into the groups and the individual distance estimates obtained from the maximum and the minimum are very coherent.

On the other hand, the absence of a period-absolute V magnitude correlation inside each group could indicate that such a relation depends on supplementary parameters. Our method divides the sample in groups with more homogeneous kinematics than the sample as a whole and so, as discussed below, with more homogeneous ages and metallicities. The fact that the period distributions of these groups are also clearly different confirms that a period-metallicity- M_v relation is in play and that, due to the homogeneity of the groups, it is somewhat lost inside them. However, taking the sample as a whole, it can be seen

Table 3. Results using m_{\max} (with period)

	group 1		group 2		group 3	
	θ_{MV}	σ	θ_{MV}	σ	θ_{MV}	σ
M_0 (m)	0.4	0.4	-2.0	0.5	-2.0	1.1
σ_M (m)	0.9	0.3	0.8	0.3	1.0	0.5
U_0 (Km s^{-1})	-15	6	-48	5	-57	39
σ_U (Km s^{-1})	40	4	12	5	128	33
V_0 (Km s^{-1})	-36	7	-37	4	-108	23
σ_V (Km s^{-1})	41	4	0	4	90	20
W_0 (Km s^{-1})	-7	4	-17	10	-7	27
σ_W (Km s^{-1})	39	5	10	8	139	27
Z_0 (Km s^{-1})	299	66	55	39	688	177
$\log(P)$	2.48	0.01	2.56	0.03	2.20	0.02
$\sigma_{\log(P)}$	0.09	0.01	0.12	0.03	0.08	0.02
m_c (m)	4	2	5	2	7	2
%	72	4	10	3	18	2

Table 4. Results using m_{\min} (with period)

	group 1		group 2		group 3	
	θ_{MV}	σ	θ_{MV}	σ	θ_{MV}	σ
M_0 (m)	6.5	0.7	2.4	0.6	1.3	0.8
σ_M (m)	1.3	0.3	0.7	0.5	0.8	0.4
U_0 (Km s^{-1})	-16	6	-50	8	-58	46
σ_U (Km s^{-1})	42	7	12	6	131	39
V_0 (Km s^{-1})	-38	7	-38	3	-109	37
σ_V (Km s^{-1})	41	5	0	3	93	31
W_0 (Km s^{-1})	-6	4	-22	12	-8	49
σ_W (Km s^{-1})	30	4	16	13	157	45
Z_0 (Km s^{-1})	1400	2800	58	34	641	316
$\log(P)$	2.48	0.02	2.55	0.03	2.19	0.02
$\sigma_{\log(P)}$	0.10	0.01	0.12	0.02	0.07	0.02
m_c (m)	12	1	9	2	12	1
%	72	4	11	2	17	3

that the short period Mira tend to be brighter (because group 3 is concentrated in short periods), in agreement with the results of Clayton and Feast (1969) and Foy et al. (1975).

5. Discussion

The results presented in the previous section clearly distinguish two significant groups in our sample of stars. The main one (group 1), constituting about 70% of the sample, has an absolute magnitude at the maximum similar to that of late disk giants and a slightly larger velocity ellipsoid. The scale height obtained for this group is characteristic of the old disk population and in good agreement with the value of $Z_0 = 240$ pc obtained by Jura and Kleinmann (1992) for the intermediate period Mira. The other (group 3) – about 17% of the sample – has a kinematics and scale height similar to those currently assigned to the hypothetical second component of the galactic disk, the extended/thick disk (E/T disk), and has a much brighter absolute magnitude. This group could also contain some halo stars, as suggested by the results in Table 2. In this case the group three is smaller than in the rest of the determinations and has more extreme kinematics – close to that of halo stars – suggesting that

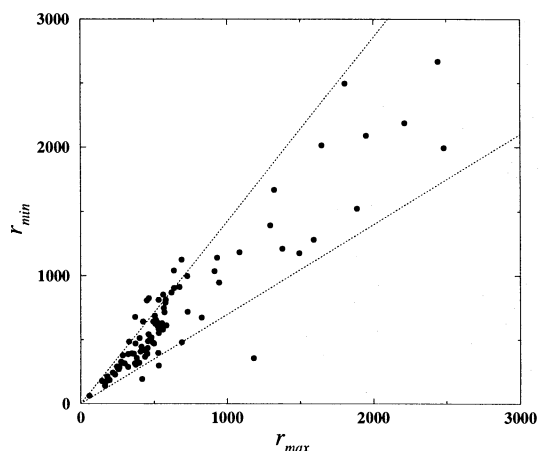


Fig. 2. Comparison of the distance estimates using the apparent magnitudes at the maximum and those using the apparent magnitudes at the minimum. Dotted lines give the limit of 30% error. Distances are given in parsecs.

a different sub-component has been detected. However, given the high estimation errors for this group and the small size of the present sample, a definitive conclusion cannot be reached.

The existence of two populations of Mira stars with different kinematics and scale height, corresponding to different components of the galactic disk, has already been indicated in some papers – see for instance the discussion in Jura (1994) –. These populations are usually characterized by having different periods, the one in the E/T disk having the shortest ones and the limit between the two being around $P=300$ days – see Jura and Kleinmann (1992) –. In our case the different distribution of periods of these two components is not assumed but directly obtained as a result, group one having a mean period around 300 days and the other group around 160 days. On the other hand, the different absolute magnitude of some short period Mira stars has also been indicated in some papers. For instance Foy et al. (1975) detected a group of high-velocity Mira stars much brighter than the normal ones at around $P=160$ days, in good agreement with our results.

There is still another group to be discussed (group 2), which is rather peculiar. Its dispersion in the V velocity seems to be very low (although the zero value obtained is probably an artifact of the method), its scale height is very small, its members tend to concentrate in two opposite directions of the sky and most of them are binary systems or belong to one. Due to these peculiarities the possibility of it being a part of a stellar current has been considered, but the uncertainties are too high to draw a conclusion about its nature. It could also be, for instance, the result of the presence of some unrelated peculiar stars in the sample forming a spurious group. It is preferable to leave its study for further works with bigger samples and better data.

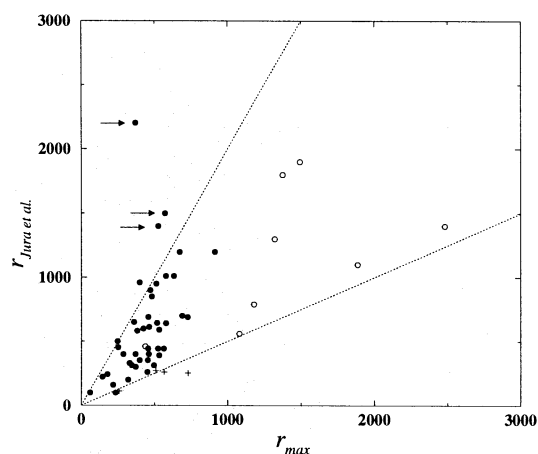


Fig. 3. Comparison of the present estimation of Mira's distances with the one given by Jura and Kleinmann (1992) and Jura et al. (1993). Filled circles correspond to group 1, crosses to group 2 and empty circles to group 3. Dotted lines give the limit of 50% error. Distances are given in parsecs.

6. Individual distances

Using the results of the Sect. 4 and the methods described in Luri et al. (1996) and references therein, the stars of our sample have been classified, assigning a group to each one. Once the star is assigned, its distance marginal density law is used to deduce both the most probable value of the distance and the estimated error. It is worth remarking that with this procedure the estimation of distances is not performed by simply using the mean absolute magnitude of each group, but that a specific, statistically correct method.

Two discriminations have been performed, one using the results for the apparent magnitudes at the maximum (Table 3) and one using the results for the apparent magnitudes at the minimum (Table 4). It is remarkable that only three stars are classified differently and that the agreement between distances estimated using m_{max} and using m_{min} is very satisfactory, as seen in Fig. 2.

The distances obtained from Table 3 were preferred to those obtained from Table 4 due to the greater reliability of the apparent magnitudes at the maximum. These distances are compared in Fig. 3 with the ones given by Jura and Kleinmann (1992) and Jura et al. (1993). In these papers the distances are estimated using K band photometry and the infrared period-luminosity relation for the Large Magellanic Cloud stars of Feast et al. (1989) – corrected to the local Milky Way metallicity – see Wood (1990) –, so using completely independent data and methods – and there are 55 stars with both distance estimations.

As can be seen in the figure, the differences between the two sets of values are under or around the 50% limit except for three stars (S Sex, U Vir and RR Boo) which are probably misclassified by our method. Indeed, they have short periods, like those of group 3, and a better agreement with Jura et al. results

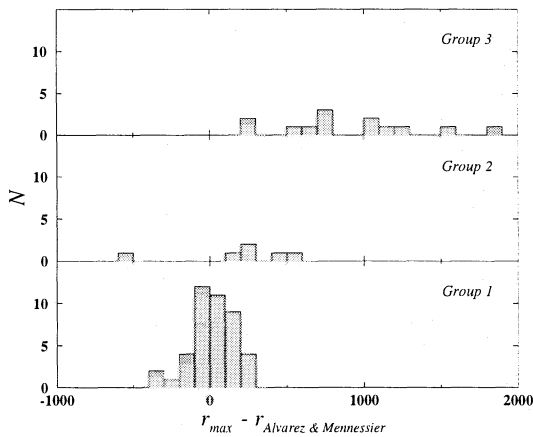


Fig. 4. Histograms of the differences between our distance estimates at the maximum and those derived by Alvarez and Mennessier (1996).

is obtained when their distances are estimated as members of this group.

The K-band photometry estimations seem systematically larger than ours for group 1. This effect can be due to uncertainties in the correction introduced by Wood (1990) to the LMC period-luminosity relation to take into account the different metallicity of the solar neighbourhood.

Another comparison is made with distance estimates by Alvarez and Mennessier (1996) that use near-infrared narrow band photometry. The histograms of the differences are shown in Fig. 4 for our three groups. The agreement is good for group 1, but there is a large discrepancy for group 3. This discrepancy is probably due to an effect of metallicity not taken into account in the Alvarez and Mennessier (1996) method and supports the idea that our classification implicitly makes a metallicity separation, related with a probable belonging to E/T disk or halo.

7. Conclusions

Using our new Maximum Likelihood method three groups of Mira stars have been detected and their luminosity, kinematics and scale height have been determined. Two of these groups have been identified with known galactic populations – the old disk population and the extended thick disk-halo population – while the third is too small to be properly defined. No period-absolute V magnitude relation has been found, probably because such a relation depends on other parameters – especially the metallicity – and due to the fact that the formed groups are more homogeneous than the Mira population as a whole.

The stars of the sample have been discriminated and their more probable distances obtained. These distances have been compared with other estimations from infrared photometry. The found discrepancies are probably explained by metallicity effects, which are not considered in these methods.

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