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Kinematics of M-Type Giant Semi-Regular Variables from the Hipparcos Catalogue

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Abstract: The kinematics of M-type (O-rich) giant semi-regular (SR) variable stars were examined. They were grouped with respect to their relative parallax errors (ϵ_π/π) in order to study the stars having relatively better parallax, and with the period limit (70 d). The spatial and velocity distributions were examined and the results were compared with the results of irregular (L) and Mira-type variables. It was found that M-type giant SR variables are distributed similarly to thin-disc stars and form a kinematically homogeneous group. When the kinematic properties of M-type giant SR variables were compared with those of L- and Mira-type variables, it was estimated that M-type giant SR variables behave as old-disc objects and their kinematic ages vary approximately between 2 and 9 Gyr.

Keywords: stars: distances — stars: late-type — stars: kinematics — stars: evolution

1 Introduction

In the General Catalog of Variable Stars (Kholopov et al. 1988, GCVS), the semi-regular (SR) variable stars are defined as intermediate (F, G, K) or late spectral-type (M, C, S) giants or supergiants. SR variables show a noticeable periodicity of light changes accompanied or interrupted by different irregularities, or even light constancy. Their periods range from 20 d to 2000 d, or more (Kholopov et al. 1988). SR variables do not form a homogeneous group and they are classified as four subtypes (SRa, SRb, SRc, SRd). This classification is not always unique and definite. The GCVS defines briefly these subgroups:

- SRa variables are late-type giants and show persistent periodicity. According to Kerschbaum & Hron (1992, 1994), SRa variables do not form a distinct class, but are probably a mixture of SRb variables and Mira variables.
- SRb variables are late-type giants with poorly expressed periodicities (Kholopov et al. 1988). Many SRb variables also have multiple periods (Mattei et al. 1998; Kiss et al. 1999).
- SRc and SRd variables will not be considered in this study because of their different physical and kinematic properties and luminosity classes (Johnson et al. 1986).

The SR designation will hereinafter indicate only semi-regular variables of type SR, SRa and SRb.

A two-colour ($V - I/B - V$) diagram, uncorrected for interstellar reddening, was plotted for all SR variables with different spectral types (F, G, K, M, C, N, R and S) in the Hipparcos Catalogue (Perryman & ESA 1997); the result is shown in Figure 1. Figure 1 shows that M-type SR

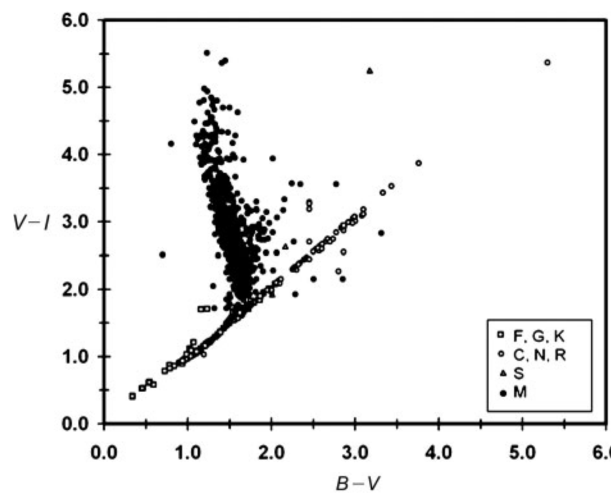

Figure 1 Two-colour diagram ($V - I/B - V$) of all SR variables in the Hipparcos Catalogue (Perryman & ESA 1997) according to different spectral types.

variables in particular behave distinctly and are well separated from the linear relation formed by the other spectral types of SR variables (Yeşilyaprak 2004). Yeşilyaprak (2004) mentions that the distributions of both Mira and L-type variables are similar to that of the of M-type SR variables shown in Figure 1.

SR and Mira variables are pulsating stars, but their evolutionary relationship is not so clear. When their luminosities, periods and period ratios were compared with theoretical models, it was identified that Mira variables pulsate in the fundamental mode while SR variables pulsate in the first, second or more (or even fundamental)

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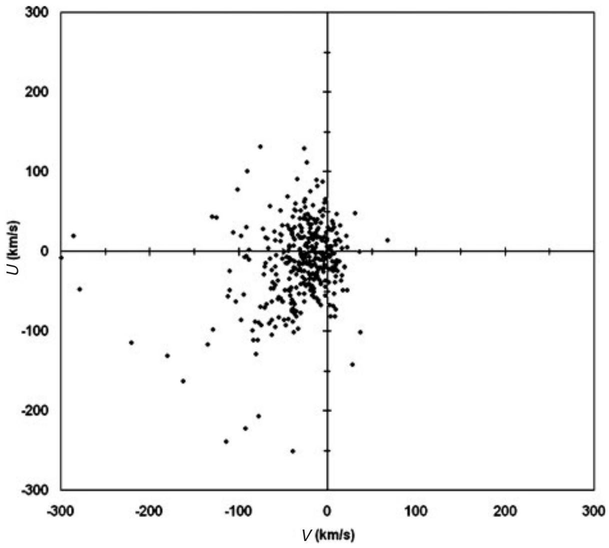

Figure 2 The $U - V$ velocity distribution of 366 M-type giant SR variables with respect to the Sun.

overtones. Bedding & Zijlstra (1998) indicated that local SR variables lie on both the Mira and second $(P - L)$ sequence of Wood & Sebo (1996) and that SR variables are Mira progenitors. In Yeşilyaprak & Aslan (2004) M-type giant SR variables obey well-defined $P - L$ relations in the Johnson and *IRAS* bands (Moro & Munari 2000). SR variables with long periods fall on the extension of the K-band $P - L$ relation for short periods (Yeşilyaprak & Aslan 2004, Figure 2).

The behaviour of SR variables with multiple periods must be related the pulsation mode changes of SR variables (Wood & Sebo 1999; Kiss et al. 1999), or to changes in stellar structure (Bedding & Zijlstra 1998), but it is not clear whether these multiple periods are the result of mode switching between Mira-like and SR-like pulsation modes (Knapp et al. 2003) or an indication of an evolutionary change into the Mira stage (Bedding & Zijlstra 1998; Wood 2000).

In Aslan (1981) the evolutionary direction was shown as Lb → SR (non-emission) → SR (emission) → Mira based on their study of mean motions and velocity dispersions. More studies of the spatial and velocity distributions of SR variables were carried out by Jura & Kleinmann (1992a,b); Chen (1998); Altmann & de Boer (2000); Mennessier et al. (2001); Yeşilyaprak (2004); Famaey et al. (2005). In addition, the kinematic ages of SR variables were examined by Olivier, Whitelock & Marang (2001); Kharchenko et al. (2002); Yeşilyaprak (2004).

The aim of this study is to investigate the kinematic properties of M-type giant SR variables having relatively better parallax in the solar neighbourhood using Hipparcos parallaxes (Perryman & ESA 1997) and to determine the kinematic ages of SR variables by means of the kinematic properties exposed, such as space velocities, velocity dispersions and metallicity.

2 The Data

The Hipparcos Catalogue (Perryman & ESA 1997) has been used primarily because it is current, fundamental and a well-measured astrometric database, especially in parallax, proper motions and photometry.

2.1 Spectral Types and Luminosity Classes

All M-type SR variables (SR, SRa, SRb) examined in this study have been selected from GCVS4 (Kholopov et al. 1988), the Hipparcos Catalogue and the New Catalogues of Suspected Variable Stars I (Kukarkin & Kholopov 1982) and II (Kazarovets, Durlevich & Samus 1988) (NSV I, II). In addition SR variables have been identified in the SIMBAD database and include all new discoveries from the Hipparcos Catalogue. AW Phe, VY Leo and V640 Her have the designation Lb (irregular) in GCVS4, but the Hipparcos Catalogue gives periods for them with classification SR. Therefore, they have been included. In the case of no information on luminosity class as a giant (III), the calculated absolute magnitudes were used as a check to exclude M dwarfs (V, VI), subgiants (IV) and supergiants (I, II). The total number of M-type giant SR variables having a parallax and consisting of only SR, SRa and SRb is 366.

2.2 Periods

The periods were taken from the Hipparcos Catalogue and GCVS4 as the main sources. In addition, the SIMBAD database and some other studies (Houk 1963; Dickinson & Dinger 1982; Armour, Henry & Baliunas 1990; Percy, Ralli & Sen 1993; Cristian et al. 1995; Percy et al. 1996; Bedding et al. 1998; Bedding & Zijlstra 1998; Koen & Laney 1998; Mattei et al. 1998; Percy & Parkes 1998; Kiss et al. 1999; Whitelock & Feast 2000; Etoka et al. 2001; Kerschbaum, Lebzelter & Lazaro 2001; Percy et al. 2001; Hinkle 2002) were used. Some of these periods are less than 20 d and even less than 10 d. The periods smaller than 20 d fall below the classical period definition of SR variables, and the nature and stability of periods much shorter than 20 d among SR variables have been questioned and remain uncertain (e.g. Mattei et al. 1998; Kiss et al. 1999; Whitelock & Feast 2000; Percy et al. 2001; Hinkle 2002; Percy & Hosick 2002, etc.), so we have excluded them from our study.

It is likely that longer periods will be more 'contaminated' with non-pulsational variations (e.g. Barnbaum, Morris & Kahane 1995; Kiss et al. 2000). Periods longer than 3000 d were excluded because the rotation periods of red variables, in theory, vary approximately between 4000 d and 10000 d, which is obviously longer than the pulsation periods of this type of stars. RY UMa can be shown as an example of this type of complex variation because of the common effect of its rotation and pulsation (Kiss et al. 2000). In addition, R Dor has two periods of about 175 d and 332 d. The mode changes of these periods occur on a time scale of about 1000 d (Bedding & Zijlstra 1998; Bedding et al. 1998).

The periods of M-type giant SR variables have been separated into subgroups such as $P < 70$ d and $P \geq 70$ d, classified according to the period-colour ($P - C$) relations, especially infrared bands (e.g. K–[12], [12]–[25] etc.) examined by Yeşilyaprak (2004). According to Kerschbaum & Hron (1992), the periods of M-type SRb variables without circumstellar dust are less than about 70 d. Additionally, it is considered that mass loss depends on luminosity and period, and a minimum period of about 70 d is a necessary condition for detectable and significant mass loss (Alard et al. 2001).

2.3 Positions, Proper Motions, Radial Velocities and Parallaxes

In the kinematic calculations of M-type giant SR variables, positions (α, δ in equatorial and l, b in galactic coordinates) and proper motions (μ_α, μ_δ) in equatorial coordinates, parallax (π) and radial velocities (V_r) of stars are used according to the Standard Model of Stellar Motion Method (SMSM) (Perryman & ESA 1997). The positions, proper motions, parallaxes and their errors were taken from the Hipparcos Catalogue, while the radial velocities were gathered from the Hipparcos Catalogue, SIMBAD database and especially updated from Famaey et al. (2005).

In order to decrease the effects of parallax errors in kinematics, SR variables having relatively better parallax have been preferred in all kinematic calculations. Therefore, to keep the statistical errors as small as possible, the relative parallax error (ϵ_π/π) was limited up to 0.150 according to Lutz–Kelker correction (Lutz & Kelker 1973; Maíz Appellániz 2004) in this study. The critical value for the relative parallax error lies between 0.150 and 0.200 (Lutz & Kelker 1973; Figure 1).

3 Method

The spatial (X, Y, Z) and velocity (U, V, W) components of a star with respect to the Sun and their errors in galactic coordinates are calculated by means of the Standard Model of Stellar Motion Method (SMSM) which was given in all details in Volume 1 of the Hipparcos Catalogue (Perryman & ESA 1997).

X and U, Y and V, Z and W are the spatial and velocity components of a star with respect to the Sun in the direction of galactic center, galactic rotation and the north galactic pole, respectively.

4 Space Motions and Distributions

4.1 Spatial and Velocity Distributions

We have first examined the spatial and velocity distributions in three dimensions and their projections onto the spatial and velocity planes. Both distributions show that M-type giant SR variables almost seem a homogeneous group kinematically as shown in Figure 2 about their $U - V$ velocity distribution.

4.2 Space Velocities

The mean space velocities and their errors ($U \pm \epsilon_U$, $V \pm \epsilon_V$, $W \pm \epsilon_W$) with respect to the Sun, the dispersions (σ_U, σ_V, σ_W) and the vertex deviation (ϕ) of M-type giant SR variables are given in in Table 1. The first row gives the results as calculated from the whole sample, whether having a period or not from the Hipparcos Catalogue and regardless of the relative parallax errors using SMSM.

Three M-type giant SR variables (Hip 72026, 79543, 115553) which have very large relative parallax errors and space velocities (exceeding 3σ) compared with other M-type giant SR variables were also excluded from the calculations. In these calculations we have not taken the differential galactic rotation (Mihalas & Binney 1981; Dehnen & Binney 1998) into account. This is not, however, expected to be significant for the present purpose, because the spatial distributions of M-type giant SR variables are not so different from each other and have not a wide range, due to the selected relative parallax error limit. It is considered that the differential galactic rotation affects all M-type giant SR variables at the same rate in this range even if it has any effect on the space velocities. Besides, according to Mihalas & Binney (1981), the differential galactic rotation is not so kinematically effective on these types of old stars.

The second row of Table 1 gives the kinematic results obtained by limiting the sample by relative parallax error ($\epsilon_\pi/\pi \leq 0.150$). The third row and fourth rows, give the results obtained by limiting the sample by the parallax error and period criteria (70 d). When the kinematic results are examined together, regardless of any criteria such as parallax error, period etc., there are some clear differences between the results and these differences result more from the errors in parallax rather than the errors in radial velocity and proper motion of M-type giant SR variables. As the Hipparcos Catalogue is still current, fundamental and a well-measured astrometric database, especially in proper motions and parallax, it is known that the errors of proper motions in Hipparcos Catalogue are quite small and better when compared with the error of parallax. The effect and importance of parallax error on kinematics are seen clearly from the kinematic results obtained, regardless of any relative parallax error and according to the relative parallax error in Table 1. In the kinematic calculations of M-type giant SR variables having relatively better parallax ($\epsilon_\pi/\pi \leq 0.150$), the results obtained are better compared to the results given in first row in Table 1, even though the errors resulting from decreasing the number of stars increase.

The kinematic results for M-type giant SR variables with $P < 70$ d and $P \geq 70$ d are given in rows 3 and 4 of Table 1. It was considered that this period was related to the mass loss (Alard et al. 2001) and the amount of circumstellar dust of SR variables (Kerschbaum & Hron 1992). This was also examined in the detailed study of Yeşilyaprak (2004) which examined period–colour ($P - C$) relations, especially in the infrared bands and the mass loss of

Table 1. The mean space velocities, velocity ellipsoids and vertex deviation of M-type giant SR variables

Group	Subgroup	N	$U \pm \epsilon_U$ (km s^{-1})	$V \pm \epsilon_V$ (km s^{-1})	$W \pm \epsilon_W$ (km s^{-1})	σ_U (km s^{-1})	σ_V (km s^{-1})	σ_W (km s^{-1})	ϕ (degrees)
SR	All	366	-15.2 ± 2.6	-30.4 ± 2.2	-9.5 ± 1.7	50.3	41.2	32.6	24.7
$\epsilon_\pi/\pi \leq 0.150$	All	64	-9.8 ± 5.8	-28.7 ± 2.9	-7.3 ± 2.3	46.3	23.1	18.7	1.7
$\epsilon_\pi/\pi \leq 0.150$	$P < 70$ d	30	-9.5 ± 6.9	-16.8 ± 4.0	-7.0 ± 3.6	38.0	22.2	19.9	-3.2
	$P \geq 70$ d	11	-22.9 ± 14.4	-29.2 ± 7.0	-14.4 ± 4.3	47.9	23.3	14.3	9.5

Table 2. The comparison of kinematic results

Study	Group	U (km s^{-1})	V (km s^{-1})	W (km s^{-1})	σ_U (km s^{-1})	σ_V (km s^{-1})	σ_W (km s^{-1})
This	SR (M III type)	-9.8	-28.7	-7.3	46.3	23.1	18.7
Yeşilyaprak et al. (2000)	L type	-11.8	-16.7	-5.5	33.6	20.5	19.1
Dehnen & Binney (1998)	Main seq.	-10.0	-5.2	-7.2	38.0	24.2	17.3
Alvarez et al. (1997)	SR + Mira	-11.0	-23.0	-12.0	37.0	22.0	20.0
Kharchenko et al. (2002)	Mira	-10.1	-90.8	-36.9	81.5	139.1	70.2
Famaey et al. (2005)	M III type	-10.2	-23.4	-7.8	36.0	22.5	18.0
Mihalas & Binney (1981)	M III type	–	–	–	31.0	23.0	16.0
Chen (1998)	Thin disc	–	–	–	36.0	21.0	17.0
	Thick disc	–	–	–	94.0	71.0	58.0
Soubiran et al. (2003)	Thin disc	–	–	–	37.0	24.0	15.0
	Thick disc	–	–	–	43.0	28.0	18.0

M-type giant SR variables. The mean space velocities according to this period criterion show some differences, but these differences may not be clear and evident to say that there is a definite kinematic difference between them, because of the number of stars in each group. So more definite period information for SR variables is needed to reveal a possible kinematic difference in this period limit.

All kinematic results given in Table 1 with respect to the period and the relative parallax error criteria indicated that M-type giant SR variables are a homogeneous group, kinematically.

M-type giant SR variables in this study were compared kinematically with the results obtained for L (Yeşilyaprak, Özdemir & Aslan 2000), SR and Mira-type variables (Alvarez et al. 1997; Dehnen & Binney 1998; Kharchenko et al. 2002; Famaey et al. 2005) in Table 2. M-type giant SR variables are different from L-type variables kinematically. Both SR and L-type variables form two distinct homogeneous groups according to Yeşilyaprak et al. (2000). When the results obtained for M-type giant SR variables were also compared with the results found for SR and Mira variables together (by Alvarez et al. 1997) and for only Mira variables (by Kharchenko et al. 2002), it was seen clearly from Table 2 that M-type giant SR variables were quite different from Mira variables, kinematically. In addition, the kinematic results of M-type giant SR variables nearly conform with the results of Dehnen & Binney (1998) and especially Famaey et al. (2005).

The mean space velocities found were evaluated together with the relation between the space velocity components (U, V, W) and $B-V$ colour for main sequence stars given in Dehnen & Binney (1998, Figure 3). It is known that the $B-V$ colour of M-type variables is less than 3.0 (Johnson et al. 1986). The $B-V$ colour of M-type giant SR variables varies between approximately 1.0 and 2.0 in this study. In the relationship between $B-V$ colour and the space velocity components for main sequence stars (Dehnen & Binney 1998, Figure 3), the values of space velocities remain almost constant, especially after approximately $B-V > 1.0$ even if the $B-V$ colour increases. The mean space velocities of M-type giant SR variables found in this study conform very well with the relation between $B-V$ colour and the space velocity components given in the study of Dehnen & Binney (1998).

4.3 Velocity Dispersions and Vertex Deviation

The velocity ellipsoids and the vertex deviation of M-type giant SR variables grouped according to the same criteria were examined and also given in Table 1. The velocity ellipsoids were evaluated together with the relation between the space velocity components (U, V, W) and the velocity dispersion parameter (S), which is accepted as a measure of the velocity dispersions for a group of stars and related to the component of the velocity ellipsoids ($S^2 = 0.77\sigma_U^2 + 0.45\sigma_V^2 + 0.79\sigma_W^2$, Dehnen & Binney 1998). The mean space velocities of M-type giant SR variables given in Table 1 fit well with the relation given by Dehnen & Binney (1998). The dispersions of M-type giant SR variables were also examined together with both the relation between the velocity ellipsoids and $B - V$ colour for main sequence stars given in Dehnen & Binney (1998, Figure 5) and the relation between $B - V$ colour and Strömberg's asymmetric drift ($V_\phi = -\sigma_U^2/80$) for main sequence stars given by Binney & Tremaine (1987) and in Dehnen & Binney (1998, Figure 5). Both the dispersions and Strömberg's asymmetric drift of M-type giant SR variables fit well with these relations.

In addition, the dispersions of M-type giant SR variables were compared with the results obtained for red variables, especially Mira and M-type variables in the different studies given in Table 2. However, the dispersions found for M III-type, SR and Mira variables and thin-disc stars are almost similar to those of M-type giant SR variables examined in our study. Other results found for only Mira and L-type variables and thick-disc stars supported the theory that M-type giant SR variables are different from Mira and L-type variables, kinematically.

4.4 Kinematic Properties

In the kinematic study of Aslan (1973) SR variables with long periods were found to be disc stars and M-type SRa variables distributed near the galactic plane. In the studies of Jura & Kleinmann (1992a,b) and Kerschbaum & Hron (1992), M-type SR and Mira variables having long periods resembled the thin-disc stars, while the same type stars having short periods were shown to be members of the thick-disc stars. Likewise, long-period variables including Mira and SR-type stars were usually defined as old-disc stars or as members of the galactic halo stars.

M-type giant SR variables were found to be disc stars when their spatial and velocity distributions were examined together. The spatial distribution of M-type giant SR variables, especially along the Z-axis, varies across the known disc region of the Milky Way, which is approximately ± 500 pc along the Z-axis (Zeilik, Gregory & Smith 1992). Furthermore, it was considered recently that the limit of the disc region reached to about ± 800 pc, according to the study of Soubiran, Bienaymé & Siebert (2003). M-type giant SR variables were considered to be old thin-disc stars when their velocity distributions and dispersions given in Table 1 were examined and evaluated together with the studies of the kinematics thin- and thick-disc stars given by Chen (1998) and Soubiran et al. (2003) in Table 2.

4.5 Kinematic Age

In order to determine the kinematic ages of the stars, some well-known kinematic properties are examined together, like spatial and velocity distribution, velocity dispersion and metallicity, etc. For example, the ages of stars increase as the value of σ_W rises and the vertex deviation decreases (Mayor 1974). In addition, it is known that the ages of stars also increase as they become increasingly distant from the galactic plane (Johnson et al. 1986; Zeilik, Gregory & Smith 1992) and their metallicity decreases (Wheeler, Sneden & Truran 1989; Soubiran et al. 2003).

The metallicity range of M-type giant SR variables found in the literature is about $-0.25 < \text{[Fe/H]} < 0.25$ and of course it is clear that these values do not represent all SR variables. In the literature, there are many different studies that define the metallicity, such as $\text{[Fe/H]} \geq -1.0$ for disc stars (Wheeler et al. 1989), $-0.7 \leq \text{[Fe/H]} \leq 0.1$ for M-type giants (Eggen & Iben 1991) and $-3.0 \leq \text{[Fe/H]} \leq -1.0$ for red giants (Chiba & Yoshii 1998). When these studies were examined together, the metallicity of M-type giant SR variables can be accepted to vary approximately between -1.0 and 0.25. It can be considered that M-type SR variables are metal-rich stars compared with other long-period or red variables such as Mira variables. The kinematic ages of SR variables regarding only the metallicity, ranged between 2 and 12 Gyr according to Eggen & Iben (1991). It is clear that it cannot be greater than 13 Gyr which is both the age of halo stars (Johnson et al. 1986; Eggen 1998; Heck & Caputo 1999) and is an age limit for disc stars determined by Wheeler et al. (1989). Moreover, the wide kinematic age interval for Mira-type variables was given as between 1 and 10 Gyr by Kharchenko et al. (2002).

In addition to the age–metallicity relation, the relation between the velocity ellipsoids and the age of both main sequence and giant stars with K- and M-type stars given in Mihalas & Binney (1981, Figures 5–7) was utilized to determine the kinematic ages of M-type giant SR variables. When the dispersions of M-type giant SR variables were examined with the age–metallicity relations mentioned above and the age–dispersions relation, it was estimated that the kinematic ages of M-type giant SR variables lie approximately between 2 and 9 Gyr. It is obvious that the ages of M-type SR variables could be less than 10 Gyr which was the estimated maximum age of Mira variables (Kharchenko et al. 2002).

According to the studies carried out by Mihalas & Binney (1981), Yeşilyaprak et al. (2000) and Kharchenko et al. (2002) based on the kinematic results and the estimated kinematic ages of SR (SR, SRa, SRb), L and Mira-type variables, Yeşilyaprak (2004) argued that the sequence L $\rightarrow$ SR $\rightarrow$ SRb $\rightarrow$ SRa(?) $\rightarrow$ Mira, being relatively from younger to older, might indicate the direction of an age sequence or evolution, even though the age sequence among SR variables was not that easy. The behavior of SRa in the age sequence is controversial or open to question, because SRa variables are not a distinct class, but probably a mixture of SRb and Mira variables (Kerschbaum & Hron 1992, 1994).

5 Conclusions

The spatial and velocity distributions, the mean space velocities, the velocity dispersions and the vertex deviation of M-type giant SR variables were examined with respect to the period limit and the relative parallax errors. The results obtained for M-type giant SR variables in this study were compared with the results of L and Mira-type variables. It was also found that M-type giant SR variables are a member of thin-disc stars and form a homogeneous group, kinematically.

In addition, the kinematic ages of M-type giant SR variables were examined by comparing the mean space velocities, the velocity dispersions and the metallicities of L and Mira variables. M-type giant SR variables were found to resemble old-disc objects and it was estimated that their kinematic ages varied approximately between 2 and 9 Gyr.

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