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On oxygen-rich SR variables in the solar neighborhood

Tuncay ÖZDEMİR*
Department of Physics, Faculty of Science and Arts, İnönü University, Malatya, Turkey

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Abstract: Brightness distribution of variable stars was investigated based on good Hipparcos parallaxes of semiregular variables (SRVs) in the solar neighborhood, and it is shown that the order of the variability types Lb, SR, SRb, SRa, and Mira is, statistically, an order of increasing brightness along the red giant branch and asymptotic giant branch. In addition, it is also shown that the majority of Miras are above and majority of SRVs are below the tip of the red giant branch. The periods of SRVs that fall in Wood's sequence C (fundamental mode) of large Magellanic clouds were identified. Statistically, the order of SR, SRb, and Mira variables with increasing period and increasing absolute magnitude is the same in six infrared (IR) band wavelengths. The slope of the P-L relation for SR + SRb variables in sequence C increases systematically with wavelength in the near IR. This indicates that circumstellar IR emission increases with increasing period from the shorter period SRVs to Miras, which is consistent with the high mass loss rate found in long period Miras. (J-K)-M_K diagram suggests that the sequence Lb, SR, SRb, SRab (emission), and Mira may be an evolutionary sequence.

Key words: Stars, distances, fundamental parameters, late-type-stars, oscillations

1. Introduction

Semiregular variables (SRVs) are long-period pulsating variables (LPVs) located at about the same region of the color–magnitude diagram as Mira variables. Wood et al. [1] showed that LPVs in the large Magellanic cloud (LMC) fall in at least five distinct period–luminosity (P-L) sequences, designated as A, B, C, E, and D, from shorter to longer periods. The first three represent radially pulsating stars on the red giant branch (RGB) or the asymptotic giant branch (AGB). Sequences A and B correspond to SRVs pulsating in the overtones. Mira variables fall in sequence C, which corresponds to fundamental mode [1,2]. Sequences E and D represent eclipsing binaries and long secondary periods, respectively [1]. The latter remains unexplained [3,4]. The period-luminosity relations are thought to be universal in spite of different ages and metallicities [5–11].

The P-L relation for oxygen-rich SRVs in the solar neighborhood was studied by several authors using Hipparcos parallaxes [10,12–14]. Glass and van Leeuwen [14], from the updated periods and revised Hipparcos parallaxes [15], show that SRVs in the solar neighborhood span the same area in the M_K-log P plane as the LMC sequences. The present sample has more SRVs with known periods and good parallaxes than used by previous studies. The main aim of this paper is to reexamine the PL(K) relation for oxygen-rich SRVs with good parallaxes. Furthermore, this paper aims to identify SRVs that fall in Wood's sequence C (fundamental mode)

*Correspondence: tuncay@inonu.edu.tr

and to compare them with local Miras. The P-L relation of these Mira sequence SRVs at six near-infrared (IR) magnitudes is also studied.

2. The sample

All M-type SRVs with designations SR, SRa and SRb, irrespective of period, and irregular variables (IRVs) with designations L and Lb were selected from the General Catalogue of Variable Stars (GCVS, [16]) in the SIMBAD database. The list was supplemented with M giants in the long-term photometry by Tabur et al. [17]. These variables were then identified in the revised Hipparcos catalogue [15] in the SIMBAD database. SRVs and IRVs with relative Hipparcos parallax uncertainties better than 20% were selected. SRVs with the relative parallaxes $\sigma_\pi/\pi \leq 0.10$ are listed in Table 1, which will be used for the analysis. Variables with 0.10 $< \sigma_\pi/\pi < 0.20$ will be used as complementary and/or supporting data. Variability of a pulsating red giant is quite often designated as L in the GCVS, due to meager set of observations. Tabur et al. [17] determined new periods for a large number of variables designated as Lb in the GCVS; they are tentatively designated as SR* in Table 1.

There is only one oxygen-rich Mira variable (R Hya) with $\sigma_\pi/\pi \leq 0.10$. The constraint was therefore relaxed and M-type Mira variables with parallaxes were selected. They are listed in Table 2 (see notes to Table 2). The main sources of periods in Table 1 are the GCVS and a long-term observational campaign by Tabur et al. [17], but other periods from the collection of Glass and van Leeuwen [14] and Percy et al. [18,19] are also tabulated. The Infrared Background Experiment (DIRBE, [20]) and the Two-Micron All-Sky Survey (2MASS, [21]) were used as photometry sources. A value of 630 Jy for the zero point of K magnitudes (WFL) in converting the DIRBE fiuxes (2.2 μm) to magnitudes. The DIRBE catalogue was used as the source of K-magnitudes because of the lower accuracy of 2MASS JHK$_S$ magnitudes [17,20]. For stars without DIRBE magnitudes, 2MASS K-magnitude was used (or magnitudes from Tabur et al. [17], see notes to Tables 1 and 2).

Interstellar extinction is small in the K-band. Tabur et al. [17] found an upper limit of A$_K$ $\approx$ 0.05 mag with $A_K \leq 0.02$ mag for 90% of their sample of nearby pulsating M giants. Therefore no correction for interstellar extinction was applied to magnitudes in Tables 1 and 2. Lutz–Kelker (LK) corrections are negligibly small for stars in Table 1 but individual LK corrections are tabulated for variables in Table 2. These values are calculated using $LK = -8.09\ (\sigma_\pi/\pi)^2$ (see WFL and references therein).

3. P-L relation

It is well known from the semiregular variability and from their multiperiodic variations [17–19,22–25] that it is not easy to represent the pulsation of a given SRV with a single period. Additionally, it is even questionable for most cases. In Table 1, all available periods known for each star are listed. The sources of the periods are explained in the notes to Table 1.

The question arises as to which period to use in the P-L diagram of SRVs. One may argue that the periods given in the GCVS ([16], SIMBAD database) would be more stable. Figure 1 shows the log PL(K) diagram for stars in Table 1 with GCVS plus six stars. These are UW Lyn, μ Gem, V669 Her, and NSV 24405 (106 Her) with more certain periods (Table 1).

It is seen in Figure 1 that a longer period group with a small number of SRVs is well separated in the diagram, at least three of which (L2 Pup, R Dor, and NSV 24405 = 106 Her) may be identified with Woods

Table 1. Semiregular variables of M type with Hipparcos parallaxes $\sigma_{\pi} / \pi \leq 0.10$.

Name	HIP	Type	SP	π (mas)	σ_{π} (mas)	K (mag)	Pgcvs (d)	Periods (days) (Percy et al.)	Periods (days) (Tabur et al.)
YY Psc	154	SR*	M3III	7.55	0.59	–0.47			23.1, 32.0, 53.6, 167.8
AE Cet	1170	SR*	M1III-M3III	7.29	0.28	0.20			19.2, 19.6, 27.1, 41.7
eta Scl	2210	SR*	M4IIIa	7.22	0.51	0.09			22.7, 23.5, 24.6, 47.3, 128.7, 158.7
TV Psc	2219	SR	M3III	6.17	0.59	–0.17	49.1	55, 550	55.1, 216.5, 266.7
V0428 And	2900	SRS	K5-M0III	5.29	0.3	1.24	11.5	11,15,22	
EL Psc	3632	SRS	M4IIIa	4.2	0.29	0.25	12	12,?,32?,40?	24.3, 25.7, 37.3, 115.2
BQ Tuc	4200	SR*	M4III	4.58	0.28	0.20			31.6, 45.0, 60.9
NSV 346	4317	SR*	M7 g, M4	5.75	0.42	1.04			18,8
CC Tuc	4879	SR*	M2III	3.76	0.32	1.57			16.2, 20.3, 20.6
NSV15347	7506	SR*	M3 III	4.37	0.32	1.41			13.9, 17.9, 23.6, 37.6, 91.7
psi Phe	8837	SR	M4III	9.54	0.19	–0.65	30		43.7, 48.1
AA Tri	9171	SRB	M5 g	5.11	0.46	0.17			23,5
AR Cet	9372	SR:	M3III	6.85	0.31	–0.39			22.0, 22.9, 28.7, 37.3, 100.7
AV Ari	10155	SRS	M3III	5.84	0.49	0.95	5.032		18.1, 21.9
NSV748	10328	SR*	M0III	6.81	0.38	1.87		32:, 275:	
TZ Hor	11293	SR*	M5III	4.33	0.41	0.78	**65***	65*	23.3, 52.9, 69.8, 116.7
CL Hyi	11455	SRB:	M6-7	6.2	0.45	0.03			66.4, 71.9, 75.8, 94.1, 100.1
TV Hor	11648	SRB	M4/M5III	3.42	0.33	1.11	30		32.9, 33.6, 34.8, 47.1, 69.9, 248.1
RZ Ari	13654	SRB	M6III	9.28	0.3	–1.03	56.5	37.7, 56.5, 370	49.9, 54.8
rho Per	14354	SRB	M4II	10.6	0.25	–1.97	50	120, 250	
NSV 15634	14456	SR*	M3 g	7.15	0.41	0.52			12.9, 31.8, 115.7, 191.9
tau4 Eri	15474	SR*	M3/M4III	10.71	0.54	–1.19			23,8
gam Ret	18744	SR	M4III	6.95	0.11	–0.47	25		30.0, 42.8, 277.0
DV Eri	21296	SR*	M3III	3.28	0.26	0.66			28.9, 44.2, 62.2
R Dor	21479	SRB	M8IIIe	18.31	0.99	–4.02	338	175b, 332b,325:s	168,9
DM Eri	21763	SRB	M3/M4III	8.85	0.6	–0.34	30		18.8, 45.5
NSV 16242	23653	SR*	M2 III	3.95	0.35	2.03			13.1, 18.4, 92.9, 109.4
WZ Dor	23840	SRB	M3III	5.77	0.18	0.33	40		26.0, 44.5
RX Lep	24169	SRB	M6III	6.71	0.44	–1.38	60	80, 99	90.1, 101.7
	25194	SR*	M1III	5.02	0.37	1.13			78.7, 156.5
WY Lep	27229	SR*	M4/M5III	5.28	0.47	0.59			32.2, 47.3, 162.9, 183.8
AF Col	29263	SR*	M2II-III	3.83	0.25	0.66			42.0, 43.9, 48.6, 112.5, 250.6
UW Lyn	29919	SR*	M3IIIab	5.11	0.33	–0.25	37.6*	26, 37.6a, 35, 49.5a,	
mu. Gem	30343	SR*	M3III	14.08	0.71	–1.88	27*	20, 27.0a, **29**, 51.	25.2, 40.5

Table 1. Continued.

Name	HIP	Type	SP	π (mas)	σ_π (mas)	K (mag)	Pgcvs (d)	Periods (days) (Percy et al.)	Periods (days) (Tabur et al.)
L2 Pup	34922	SRB	M5IIIe	15.61	0.99	–2.41	140.6		
MZ CMa	35626	SRB	M3III	5.1	0.37	*1.21*			15.8, 17.6, 18.7, 23.9, 25.6, 34.9, 49.6
VZ Cam	36547	SR	M4IIIa	6.53	0.25	–0.04	23.7		27.1, 28.1, 38.5, 39.0, 54.4, 205.3, 249.4
DU Lyn	37946	SRB	M3III	7.53	0.4	0.90		22: 36	
BC CMi	38406	SRB	M4III	6.45	0.47	0.79	35	19, 20:,30?, 28:a, 34.1, 45:	27.7, 143.3, 208.3
BP Cnc	41400	SRB	M3III	3.62	0.33	0.71	40		
AK Hya	42502	SRB	M6III	6.4	0.41	–0.61	75	50::	*78.6, 88.7, 133.7*
AK Pyx	43215	SR*	M5III	4.68	0.41	0.57			55.5, 57.9, 86.7, 162.9, 232.6
FZ Cnc	44126	SRB	M4IIIvar	5.32	0.44	1.23			17,6
RS Cnc	45058	SRC:	M4III	6.97	0.52	–1.60	120	225, 137:	
GK Vel	46194	SRB	M3III-M5III	4.46	0.38	1.04	120		
GY Vel	50332	SR*	M4.5III	4.56	0.33	0.43			20.0, 25.3, 25.9, 26.5, 35.7, 36.7, 116.6
V0505 Car	51141	SRB	M3III	3.15	0.29	1.84			26,5
RX LMi	52366	SRB	M2III	4.02	0.33	1.07	150		
VY Leo	53449	SR*	M5.5III	8.39	0.37	–0.79			35.8, 54.9, 75.0, 84.5
NSV 18788	56293	SR*	M1-2 III	4.54	0.36	1.57			16.7, 18.3, 24.6, 28.5, 34.9, 133.0
V0913 Cen	56702	SR*	M4III	6.08	0.52	*0.03*			34.0, 70.6, 247.5
ome Vir	56779	SR*	M4III	6.56	0.36	–0.24		30, 275	23.9, 25.0, 29.5, 31.0, 59.0
nu. Vir	57380	SRB	M1 III	11.1	0.18	0.09			11.1, 12.3, 16.8, 23.7
DU Cha	57505	SR*	M6III	4.42	0.39	0.35			58.0, 60.1
II Hya	57613	SRB	M4III	5.98	0.27	–0.31	61		29.5, 30.4, 39.5, 41.4, 89.1
eps Mus	59929	SRB:	M5III	10.82	0.17	–1.50	40		32.1, 32.7, 42.5, 43.7, 44.9, 46.0, 63.4, 196.5
BL Cru	60781	SR:	M4/5III	7.36	0.32	–0.19			30.7, 42.3, 43.6
V0928 Cen	60979	SRB	M2II-III	4.42	0.37	1.16			19.0, 19.2, 22.3, 24.6, 29.6, 46.4, 102.2
gam Cru	61084	SR*	M4 III	36.83	0.18	–3.17			12.1, 15.1, 16.5, 54.8, 82.7, 104.9
FW Vir	61658	SRB:	M3IIIab	6.62	0.31	0.94	15		
V0341 Hya	61908	SRB	M3III	4.32	0.43	1.72			8.6, 18.3, 18.7, 36.2, 216.5, 281.7
LM Mus	62247	SRB	M5III	4.87	0.47	*1.40*			20.8, 28.9, 30.0, 30.5, 42.4
psi Vir	62985	SR*	M3III	5.99	0.23	0.14			22.4, 23.5, 24.5, 30.1, 31.3, 49.4, 162.6
TU CVn	63024	SRB	M5III	4.69	0.32	–0.13	50	**44.5**, 230:	
NSV 6026	63090	SR*	M2-3 III	16.44	0.22	–1.24			13.0, 17.2, 25.6, 110.1, 125.8
FS Com	63950	SRB	M5III	4.43	0.41	–0.20	58	38.2, 55.4, 680	33.7, 44.6, 46.8, 159.5
NSV 6173	64852	SR*	M2 g	4.83	0.19	0.49			23.4, 24.3, 27.9, 34.1, 35.8, 64.0, 165.3
NSV 6212	65311	SR*	M1-2 III	3.99	0.34	1.70			17.9, 21.7, 22.4, 22.7, 31.7, 34.0, 52.2, 99.7
V0744 Cen	66666	SRB	M5III	6.35	0.33	–0.72	90		95.8, 102.2, 166.9

Table 1. Continued.

Name	HIP	Type	SP	π (mas)	σ_π (mas)	K (mag)	Pgcvs (d)	Periods (days) (Percy et al.)	Periods (days) (Tabur et al.)
NSV 6442	67288	SR*	M1-2 III	4.82	0.39	1.01			18.3, 18.5, 18.8, 25.4, 25.9, 50.2
V0806 Cen	67457	SRB	M4.5III	17.82	0.21	–1.67	12		26,5
tet Aps	68815	SRB	M6.5III:	8.84	0.49	–2.02	119		100.9, 111.0
ET Vir	69269	SRB	M1III	7.08	0.32	0.58	80		22.6, 23.8, 36.4, 37.6, 39.8, 48.8, 259.1
CY Boo	69829	SRB	M3III	4.28	0.41	1.52	23	**23,** 350	
W Boo	71995	SRB	M3III	4.63	0.28	0.23	25		
V0768 Cen	72432	SRB	M3III	6.34	0.34	–0.44			41.4, 57.4, 60.9, 145.1, 191.2
RR UMi	73199	SRB	M4.5III	7.1	0.37	–0.98	43.3		
sig Lib	73714	SRB	M3/M4III	11.31	0.25	–1.40	20		
tau4 Ser	76423	SRB	M5II-III	4.86	0.46	–1.02	100		86.7, 173.0, 244.5
LY Ser	76573	SR*	M4III	4.75	0.47	–0.46			66.7, 76.5, 220.8
X Her	78574	SRB	M6e	7.3	0.4	–1.49	95	102k, 178k	
LQ Her	79349	SR*	M4IIIa	4.78	0.31	0.15			24.5, 25.1, 28.0, 29.9, 33.6
del1 Aps	80047	SR*	M4-M5III	4.28	0.16	–0.79			68.0, 94.9, 101.7
V2105 Oph	80620	SRB:	M2.5III	5.65	0.39	0.48			20.5, 21.2, 21.4, 41.6, 206.6
g Her	80704	SRB	M6III	9.21	0.18	–2.05	89.2	60, 90k, 93*, 834	
NSV 7950	82028	SR*	M3 g, M4	7.19	0.42	*0.90*			13.2, 14.7, 17.1, 21.9, 38.7
V2113 Oph	84780	SR:	M5III	6.43	0.52	–0.21			47.3, 49.3, 70.5, 76.1, 257.1
V0656 Her	84833	SR*	M2IIIab	6.8	0.36	0.89			22.3, 93.9, 176.1, 234.7, 283.3
NO Aps	85760	SR	M3III	3.69	0.28	0.75			26.2, 26.6
V0642 Her	85934	SRB	M4IIIa	5.42	0.52	0.95	35.7*	25.6, 35.7a	21.9, 25.5, 33.6, 35.4, 61.2, 130.5, 153.4, 229.9
NSV24005	87390	SR*	M2 III	5.77	0.56	*1.37*			14.1, 28.5
OP Her	87850	SRB	M5II-III	3.37	0.27	0.12	120.5		
V0669 Her	89172	SR*	M3III	5.99	0.22	0.33	27*	**27**	22.9, 24.0
NSV 24405	89861	SR*	M1 III	8.32	0.29	1.02	40*		
V4401 Sgr	91135	SRB	M3/M4III	6.46	0.56	*0.74*			18.8, 23.1, 23.8, 24.2, 33.4, 35.9
V4405 Sgr	92079	SRB:	M2/3 III	4.49	0.4	*0.52*			21.3, 26.2, 32.6, 38.8, 66.9
R Lyr	92862	SRB	M5III	10.94	0.12	–2.06	46	46, 64.3	
V0387 Vul	93270	SR*	M3III	4.63	0.41	0.97			15.8, 19.2
V1743 Cyg	96198	SRB:	M4.5III	2.46	0.2	*0.75*	40		
V0450 Aql	96204	SRB	M8V	4.94	0.47	*–0.18*	64.2	65	
V0973 Cyg	97151	SRB	M4III	3.98	0.39	1.52	40	**35, 376**	
VZ Sge	98438	SR*	M4III	3.2	0.31	*0.12*			36.5, 39.2, 51.4, 65.1
NU Pav	98608	SRB	M6III	6.86	0.26	–1.47	60		59.0, 62.0, 87.0, 124.7, 272.5
V3872 Sgr	98688	SR*	M4III	7.27	0.18	–0.76			24.0, 30.4, 31.3, 42.8, 50.5, 234.7

Table 1. Continued.

Name	HIP	Type	SP	π (mas)	σ_π (mas)	K (mag)	Pgcvs (d)	Periods (days) (Percy et al.)	Periods (days) (Tabur et al.)
EU Del	101810	SRB	M6III	8.56	0.5	–1.01	59.7	61.6, 62k	44.0, 60.8, 67.3, 132.6, 235.3
EN Aqr	102624	SR *	M3III	5.57	0.28	–0.22			20.2, 24.9, 27.2, 35.0, 36.9, 143.9, 197.2
NSV13620	104974	SR*	M2 III	5.33	0.33	0.54			19.5, 20.1, 24.3, 91.5
V1070 Cyg	105562	SRB	M7III	6.22	0.44	–0.60	73.5	42:, 50, 60,64, 100:, 110,470	
SX Pav	106044	SRB	M5III	7.92	0.28	–0.78	50		36.0, 50.6, 53.1, 77.6, 88.9
NV Peg	106062	SRB	M4.5III	4.9	0.32	–0.16			44.0, 45.4, 77.0, 91.5
W Cyg	106642	SRB	M4e-M6e(Tc:)III	5.72	0.38	*–1.41*	131.1	130.4, 240k, 250:	
V1339 Cyg	107140	SRB	M4III:	4.77	0.35	*0.21*	35		
EP Aqr	107516	SRB	M8IIIvar	8.8	0.63	–1.53	55		81.8, 117.9, 125.8
eps Oct	110256	SRB	M5III	11.22	0.23	–1.16	55		18.0, 23.1, 23.4, 201.6
del2 Gru	111043	SR*	M4.5IIIa	9.88	0.23	–0.89			20.6, 24.1, 24.5, 32.3, 33.3, 97.6, 125.9, 205.8
nu. Tuc	111310	SR*	M4III	11.24	0.23	–0.14			22.3, 24.4, 24.8, 25.1, 25.5, 33.8, 50.6, 80.1, 123.2, 261.8
bet Gru	112122	SR*	M3-5II-III	18.43	0.42	–3.21			28.1, 37.1, 37.7, 38.4, 39.2, 39.7, 105.6, 232.6
lam Aqr	112961	SR*	M2III	8.47	0.66	–0.64			24.5, 32.0, 49.5
bet Peg	113881	SR*	M2.5II-III	16.64	0.15	–2.25			43,3
GZ Peg	114347	SRA	M4SIII	4.17	0.34	–0.45	92.66	129	40.1, 42.2, 46.5, 49.4, 80.3
khi Aqr	114939	SRB:	M3III	5.32	0.37	–0.29	35.25		32.3, 38.5, 44.9
HW Peg	116264	SR*	M5IIIa	6.27	0.28	–0.18			30.7, 41.7, 43.2
NSV 26103	116307	SR*	M3 g	3.6	0.35	1.04			34.7, 102.7
XZ Psc	117887	SR*	M5IIIb	5.12	0.41	0.13			21.1, 40.2, 113.5
V0363 Peg	117986	SRB	M4	4.93	0.4	1.27			21.9, 22.7, 32.3, 33.0
psi Peg	118131	SR*	M3 III	6.85	0.24	0.02			37.4, 118.9

Notes: Percy et al.: Periods from Percy et al. [35–38] as tabulated by Glass and van Leeuwen [14] and from Percy et al. [18,19]. An "a" and asterisk denote first rank and most stable periods. The most secure periods given are in bold; most uncertain periods are marked with a colon or with a question mark. Periods marked with "k" are from Kiss et al. [23]. P: Periods from Tabur et al. [17]. Italic K magnitudes are from 2MASS, and underlined values are from Kiss et al. [23].

Table 2. Mira variables of M type with Hipparcos parallaxes $\sigma_\pi/_\pi \leq 0.33$.

Name	HIP	SType	π	σ_π	K	Ko	Log P	MK
omi Cet	10826	M7IIIe	10.91	1.22	–2.43	–2.5	2.521	–7.24
R Hor	13502	M7IIIe	4.76	0.97	–1.15		2.610	–7.76
R Aur	24639	M7III	7.63	1.28	–0.58		2.660	–6.17
R Car	46806	M6.5IIIpeva	6.34	0.81	–1.12	–1.4	2.490	–7.11
R Leo	48036	M8IIIe	14.03	2.65	–2.72	–2.6	2.491	–6.98
S Car	49751	M2.5IIIe	1.83	0.57	*1.86*		2.175	–6.83
R Hya	65835	M7IIIe	8.05	0.69	–2.37	–2.5	2.590	–7.84
R Cen	69754	M5IIevar	2.6	0.76	*–0.65*		2.737	–8.57
U UMi	69816	M6e	3.8	1.07	0.83		2.520	–6.28
S CrB	75143	M7e	**2.38**	**0.17**	0.30	0.32	2.556	–7.81
U Her	80488	M7III	**3.81**	**0.26**	–0.38	–0.3	2.609	–7.48
RR Aql	98220	M7e	**1.59**	**0.40**	0.55	0.46	2.595	–8.44
T Cep	104451	M7IIIe	5.33	0.90	–1.59		2.589	–7.96
R Cas	118188	M7IIIe	**7.46**	**0.90**	–1.92	–1.8	2.634	–7.55
UX Cyg		M5	**0.54**	**0.06**	1.76	1.93	2.752	–9.58

Notes: The absolute magnitude M_K does not include the LK correction given in column 6. Parallax of UX Cyg is the very long baseline interferometry (VLBI) parallax from Kurayama et al. [39]. A parallax in bold face is the weighted average of Hipparcos and VLBI parallax, the weight being the inverse square of the parallax error. VLBI parallaxes are from [40] (S CrB, U Her, RR Aql) and [41] (R Cas). Italic K magnitudes (S Car and R Cen) are from 2MASS. The stars O Cet, R Car, R Leo, R Hya, and R Cas were used by WFL for the zero point of PL(K) relation.

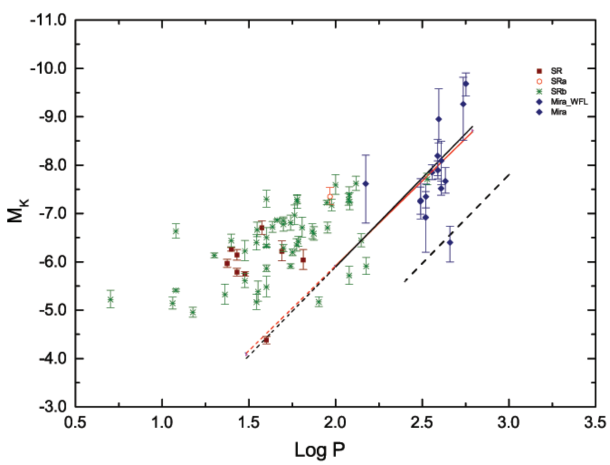

Figure 1. Log P–M_K diagram for oxygen-rich SRVs with Hipparcos parallaxes with $\sigma_\pi/\pi \leq 0.10$ and with periods from GCVS, plus six more stars with first rank or more stable periods marked (Table 1) (see notes to Table 1) and Mira variables (Table 2). The solid line is the Mira PL(K) relation for the LMC sequence C by Ita and Matsunaga [27], with the distance modulus of 18.50; the red line is the relation for the Galactic AGB variables (Mira and SR) from WFL, the dotted lines being their extrapolations to log P < 2. The dashed line on the right is the PL(K) relation for the sequence D by Ita et al. [26].

sequence C represented by the solid line. There is no obvious indication of the sequences C, B, and A (see Ita et al. [6]), due perhaps to dispersions caused by the parallax errors and observational errors in the K magnitudes (see also Tabur et al. [10]).

The majority of Miras fall to the right of the PL(K) relation in Figure 1. Two of them, R Aur and U UMi, appear to be members of the Woods sequence D represented by the dashed line on the right, but an independent check is needed.

All periods in Table 1 are plotted in Figure 2; there are up to six periods for a given star and the filled dots denote the shortest period. Assuming that the majority of multiple closely spaced periods probably represent the same oscillation mode [10], all adjacent periods of a given star with the ratio of $P_{long} / P_{short} < 1.11$ are represented by one period in order to reduce crowding. The filled triangles denote the Mira variables in Table 2. The position of the LMC sequences C and D by Ita et al. [26] is shown as dotted boxes, adopting 18.50 for the distance modulus of LMC. The solid line is the PL(K) relation by Ita and Matsunaga [27] for LMC sequence C, the dashed line being its extrapolation to shorter periods. There is no obvious indication of the individual sequences, but the distribution of points in Figure 3 spans all the LMC period-luminosity sequences (see also [14]), Figure 1. The majority of Miras and a good fraction of SRVs are above the tip of the red giant branch (TRGB) indicated by the horizontal dotted line [28] (see Table 3 below).

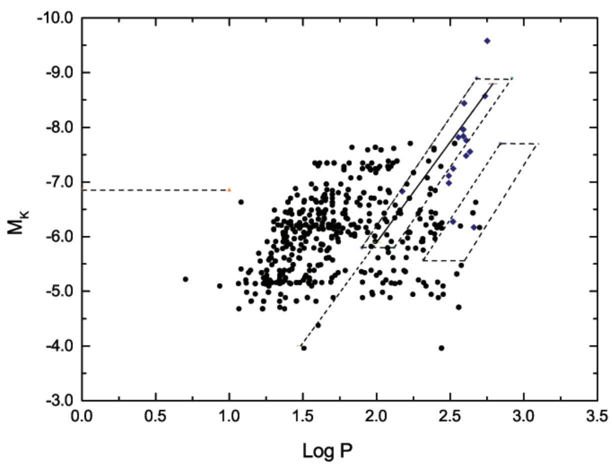

Figure 2. Log P–M_K diagram for all stars with all the available periods in Table 1. The positions of the LMC sequences C and D by Ita et al. [26] are shown as dotted boxes. The solid line is the PL(K) relation by Ita and Matsunaga [27] for LMC sequence C, the dashed line being its extrapolation to shorter periods. The diamonds denote the Mira variables in Table 2. The brightest Mira, with log P = –2.752 and M_K = –9.58, is Mira UX Cyg. (Figures 3 and 4). The position of the TRGB from revised Hipparcos parallaxes [28] is marked by the dotted horizontal line.

Table 3. Fraction of variables above the TRGB according to variability type for two relative parallax limits. The limit for Miras is $\sigma_\pi / \pi < 0.33$. n is the number of variables above TRGB out of N variables.

	$\sigma_\pi/\pi < 0.10$			$\sigma_\pi/\pi < 0.20$		
Type	N	n	%	N	n	%
Lb	24	2	0.08	141	17	0.12
SR	61	4	0.07	92	9	0.10
SRb	64	14	0.22	117	30	0.26
SRa	1	1	1	5	3	0.60
Mira				15	12	0.80

4. Color-magnitude diagram

The (J-K)-M$_K$ diagram of the SRVs (Table 1) and Mira variables (Table 2) is given in Figure 3, where variables of type Lb with parallaxes $^{\sigma_\pi}/_{\pi} \leq 0.10$ are also plotted. It is seen in Figure 3 that the order of variability, on average, tends to be Lb, SR, SRb, and Mira.

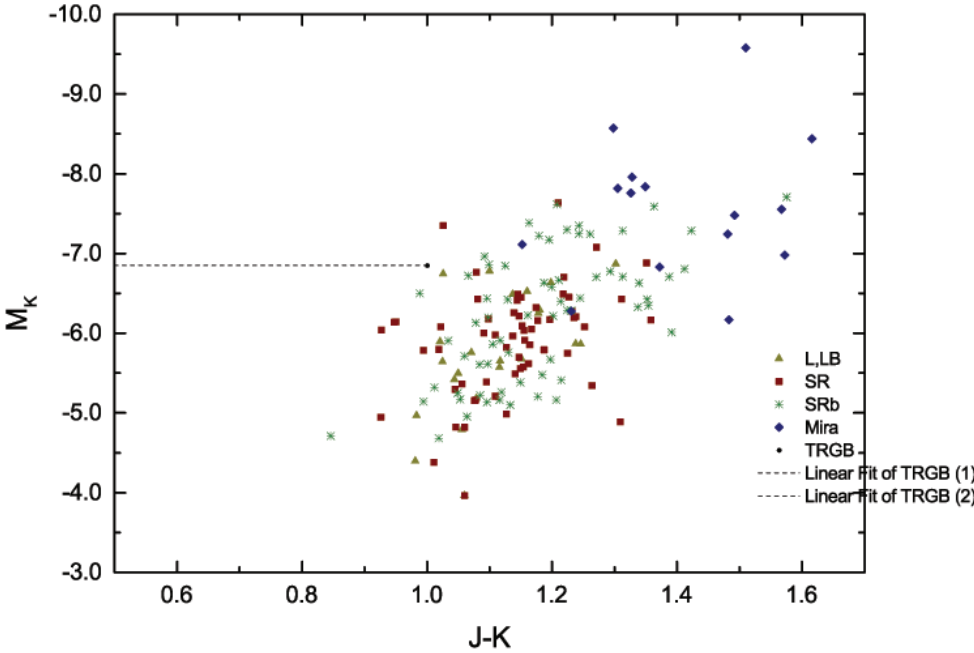

Figure 3. (J-K)-M$_K$ color-magnitude diagram of Lb, SR, SRb variables with $\pi \geq 10\sigma_\pi$ and Mira variables with $\pi \geq 3\sigma_\pi$. The dotted line shows the position of the TRGB.

It is apparent from Figure 1 that this is also the order of increasing period (see [26] for period-(J-K) relation). The relevant statistics for two relative parallax limits are given in Table 3, where N is the total number of stars of each type and n is the number of stars above the TRGB. The majority of Miras are above the TRGB and are AGB stars, and the majority of SRVs are below the TRGB, which may mostly be RGB stars. The median periods for the present limited sample of SR and SRb stars in Table 3 are 112 and 141 days, respectively. According to Kholopov et al. [29], the SRb, SRa, and Mira distributions peak at periods around 100, 150, and 270 days, respectively. It may be concluded that percentage of variables above the TRGB increases with period. Note the small number of stars in Table 3.

5. The Mira sequence

As noted above, the distribution of points in Figure 2 spans all the LMC P-L sequences. These sequences will not be identified here, but it is of more interest to know which SRVs, or better, which periods, fall in sequence C (Mira sequence), marked in Figure 2. It is also important to compare the properties of these SRVs with Miras, which pulsate in the fundamental mode [1]. A well-known example is R Dor: Bedding et al. [12] found that it switches back and forth between a large amplitude mode (Mira mode) with a period of 332 days, and a smaller amplitude mode with a period of 175 days (see also Price et al. [30]).

The expected positions of sequence C defined by Ita et al. [26], shown in Figure 2, and by Riebel et al. [31] (not shown) do not quite agree: the former is narrower in shorter period side than the second. The narrower definition by Ita et al. [31] and its extension to shorter periods were adopted, and SRVs falling in that fundamental mode sequence were selected, under the assumption that they are fundamental pulsators. They are tabulated in Table 4, where the periods are designated as P_0. Out of the 126 SRVs in Table 1, 31 fall in this fundamental mode sequence with a single period and only two SRVs, W Cyg and CL Hyi, with two periods. Moreover, there are 22 SRVs out of 90 SRVs with $0.10 < \sigma_\pi/\pi < 0.20$ (not listed here) that fall in this box. New observations would be useful to check on the stability of these periods.

Table 4. SRVs with $^{\sigma_\pi}/_{\pi} \leq 10$ that fall in the Mira sequence and its extension to shorter periods.

Name	HIP	Var	Spec.	π	σ_π	K	M_K	Log	P_0
		Type	Type	mas	mas	Mag	mag	P_0	(day)
NSV15347	7506	SR*	M3III	4.37	0.32	1.41	-5.39	1.962	91.7
AR Cet	9372	SR:	M5III	6.85	0.31	-0.39	-6.21	2.003	100.7
NSV748	10328	SR*	M0III	6.81	0.38	1.87	-3.96	1.505	32.0
TZ Hor	11293	SR*	M5III	4.33	0.41	0.78	-6.04	2.067	116.7
CL Hyi	11455	SRB:	M6/M7	6.2	0.45	0.03	-6.01	1.987	97.0
R Dor	21479	SRB	M8IIIe	18.31	0.99	-4.02	-7.71	2.529	338.0
SW Col	25194	SR*	M1III	5.02	0.37	1.13	-5.36	1.896	78.7
AF Col	29263	SR*	M2II-III	3.83	0.25	0.66	-6.43	2.051	112.5
L2 Pup	34922	SRB	M5IIIe	15.61	0.99	-2.41	-6.44	2.148	140.6
AK Hya	42502	SRB	M6III	6.4	0.41	-0.61	-6.58	2.126	133.7
RS Cnc	45058	SRC:	M6IIIase	6.97	0.52	-1.60	-7.39	2.352	225.0
GK Vel	46194	SRB	M3III	4.46	0.38	1.04	-5.71	2.079	120.0
GY Vel	50332	SR*	M4.5III	4.56	0.33	0.43	-6.27	2.067	116.6
V0928 Cen	60979	SRB	M2II-III	4.42	0.37	1.16	-5.61	2.009	102.2
gam Cru	61084	SR*	M3.5III	36.83	0.18	-3.17	-5.34	1.918	82.7
FS Com	63950	SRB	M5III	4.43	0.41	-0.20	-6.96	2.203	159.5
V0744 Cen	66666	SRB	M5III	6.35	0.33	-0.72	-6.70	2.222	166.9
ET Vir	69269	SRB	M1III	7.08	0.32	0.58	-5.17	1.903	80.0
V0768 Cen	72432	SRB	M3III	6.34	0.34	-0.44	-6.43	2.162	145.1
tau4 Ser	76423	SRB	M5II-III	4.86	0.46	-1.02	-7.59	2.388	244.5
LY Ser	76573	SR*	MIII	4.75	0.47	-0.46	-7.08	2.344	220.8
X Her	78574	SRB	M8	7.3	0.4	-1.49	-7.17	2.250	178.0
V0642 Her	85934	SRB	M4III	5.42	0.52	0.95	-5.38	1.787	61.2
NSV 24405	89861	SR*	M0III	8.32	0.29	1.02	-4.38	1.602	40.0
NU Pav	98608	SRB	M6III	6.86	0.26	-1.47	-7.29	2.435	272.5
EU Del	101810	SRB	M6III	8.56	0.5	-1.01	-6.35	2.123	132.6
EN Aqr	102624	SR *	M3III	5.57	0.28	-0.22	-6.49	2.158	143.9
NSV13620	104974	SR*	M2III	5.33	0.33	0.54	-5.82	1.961	91.5
W Cyg	106642	SRB	M4III	5.72	0.38	-1.41	-7.62	2.380	240.0
nu. Tuc	111310	SR*	M4III	11.24	0.23	-0.14	-4.89	1.704	50.6
bet Gru	112122	SR*	M5III	18.43	0.42	-3.21	-6.88	2.367	232.6
XZ Psc	117887	SR*	M5III	5.12	0.41	0.13	-6.32	2.055	113.5
psi Peg	118131	SR*	M3III	6.85	0.24	0.02	-5.80	2.075	118.9

Figure 4 shows these Mira-like variables (Table 4) plus all Mira variables (Table 2) in the log P_0-M_λ plane for J, H, K, 3.5, 4.9, and 12 μm. The 2MASS magnitudes J and H, and fiuxes at K (2.2 μm), 3.5, 4.9, and 12 μm are all taken from the DIRBE catalogue ([20], SIMBAD database); their magnitude zero points are approximately the same as given by Smith et al. [20]. The crosses denote Mira variables in Table 2, including those used by WFL in evaluating the mean galactic PL(K) relation zero-point, and filled green dots denote the two Miras, R Aur and U UMi, which fall in sequence D (see also Figure 1). Symbols in other panels for SR, SRb, and Miras are the same.

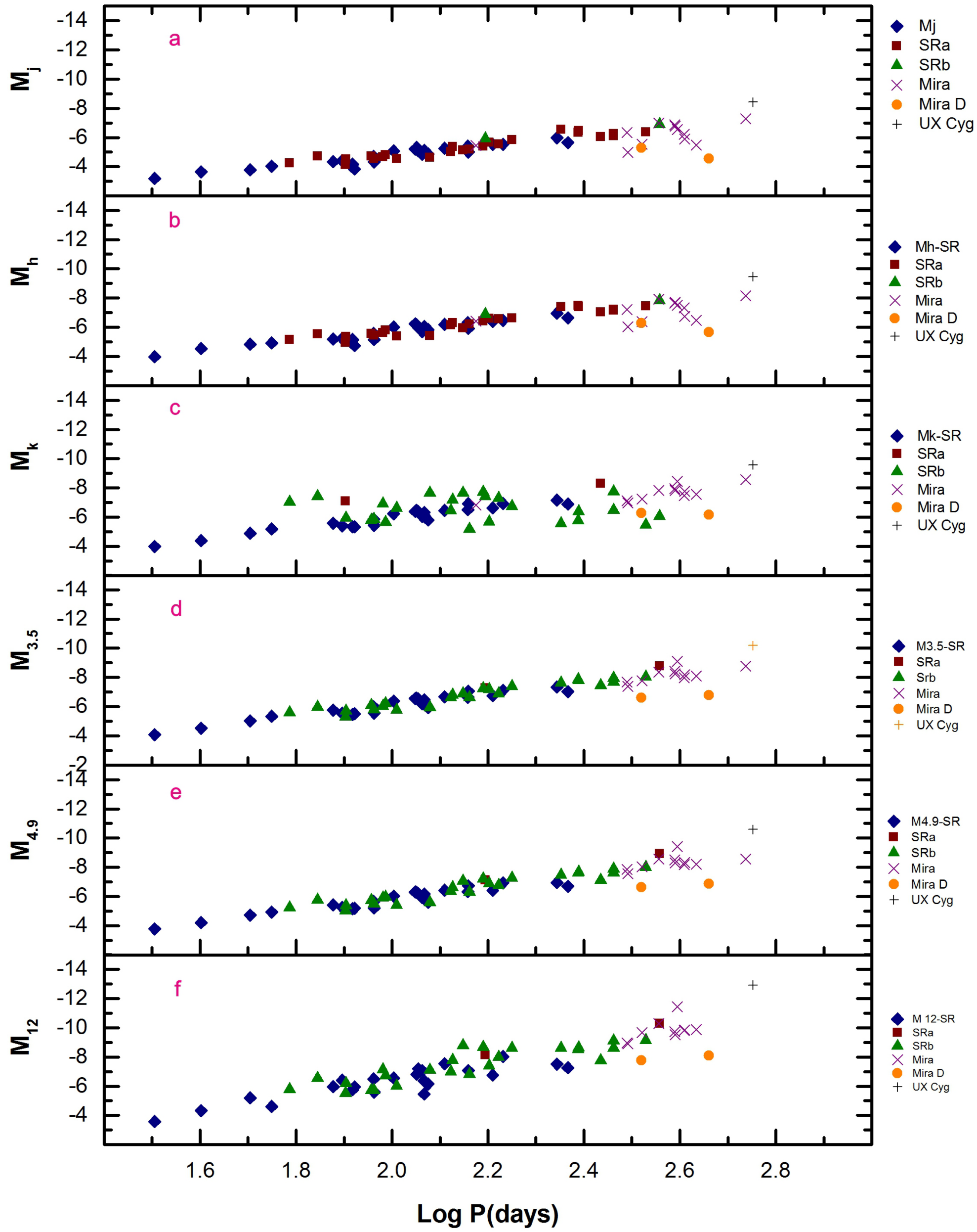

Figure 4. P-L relations for J, H, K, 3.5, 4.9, and 12 μm for SRVs that are members of fundamental mode sequence (Figure 2) and all Miras (Table 2). The red circles are two Miras that appear to fall in sequence D (Figure 2).

The panel for M_K (third from top) of Figure 4 is admittedly a P_0-L(K) relation of fundamental pulsator SRVs by definition and is not a proof of a real relation for SRVs. Figure 4 gives log $P_0 - M_\lambda$ diagrams of the same SRVs in several IR bands. All the IR panels are quantitatively similar and have more information. The main feature is that SRVs fall in lower parts of sequence C than Miras, similar to those in the LMC [32], The order of SR, SRb, and Mira variables with increasing period and increasing absolute magnitude is the same, on average, on all panels of Figure 4 (see Figures 1–3). Assuming that this increase with period is linear, a linear fit was applied to each panel (Miras excluded). Table 5 tabulates the slopes for SR variables in column 2, for SRb variables in column 3, and SR and SRb variables combined in column 4. Taken at their face value, slope increases systematically with wavelength and that the slope for SRb is systematically larger than for SR, indicating that circumstellar IR emission increases more with increasing period [27,31,33] and that this effect is more for SRb than SR. As clearly seen in Figure 4, this is supported by the increasing shift of Miras and one SRa variable, W Hya, at the long period end, to brighter magnitudes with respect to SRVs with increasing wavelength.

Table 5. The slopes of $M_\lambda = a \log P_0 + b$ for SRVs with $\sigma_\pi / \pi < 0.20$ (see text).

λ	SR	SRb	SR + SRb
J	–3.16 ± 0.26	–3.45 ± 0.24	–3.32 ± 0.15
H	–3.27 ± 0.26	–3.71 ± 0.26	–3.51 ± 0.17
K	–3.67 ± 0.22	–3.74 ± 0.24	–3.73±0.15
3.5 μm	–3.72 ± 0.23	–3.89 ± 0.25	–3.85 ± 0.16
4.9 μm	–3.75 ± 0.24	–4.19 ± 0.31	–4.08 ± 0.19
12 μm	–4.54 ± 0.49	–4.84 ± 0.58	–5.04 ± 0.38

The order L, SR, SRb, and Mira is an order of increasing regularity in the observed light curves. The evolutionary models of Lebzelter and Wood [34] show that LPVs first pulsate in an overtone mode and switch to fundamental mode pulsation when crossing some luminosity limit. The order Lb, SR, SR b, SR ab (emission), and Miras in Table 3 may be a suggestive of evolutionary sequence.

6. Conclusions

From Hipparcos parallaxes of SRVs in the solar neighborhood, it is shown that, statistically, the sequence of the variability types Lb, SR, SRb, SRa, and Mira is an order of increasing brightness along the RGB and AGB, and that the majority of Miras are above the TRGB and majority of SRVs are below the TRGB. Then it is possible that the stars below the TRGB may mostly be RGB stars.

The periods of SRVs that fall in Woods sequence C (fundamental mode) were identified and compared with local Miras, though the Mira sample used is much smaller than that of SRVs. The PL(K) relation (Figure 4) shows that SRVs fall in the lower parts of sequence C, similar to those in the LMC [32]. The order of SR, SRb, and Mira variables with increasing period and increasing absolute magnitude is, statistically, the same in all IR wavelengths. The slope of the P-L relation for SR + SRb variables in sequence C increases systematically with wavelength in the near-IR. This indicates that circumstellar IR emission increases more with increasing period from the shorter period SRVs to Miras.

The color–magnitude diagram (Figure 3) suggests that the order Lb, SR, SRb, SRab (emission), and Mira may be an evolutionary sequence.

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