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PHYSICAL PARAMETERS OF THREE FIELD RR LYRAE STARS[1]

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RESUMEN

La fotometría Strömgren $uvby-\beta$ de las estrellas clasificadas como RR Lyrae RU Piscium, SS Piscium and TU Ursae Majoris, ha sido empleada para estimar la abundancia de hierro, la temperatura efectiva, la gravedad superficial y la magnitud absoluta. Se discute la variabilidad secular del período de pulsación. El enrojecimiento de cada estrella se ha estimado a partir de los colores de Strömgren y de mapas celestes de enrojecimiento. Se reportan y comparan los resultados para [Fe/H], $T_{\rm eff}$ y $\log(g)$ obtenidos por alguno de los siguientes métodos: Descomposición de Fourier de la curva de luz, el índice ΔS de Preston y la comparación con las mallas teóricas en el plano $(b-y)_{\rm o} - c_{1{\rm o}}$.

ABSTRACT

Strömgren $uvby-\beta$ photometry of the stars classified as RR Lyrae stars RU Piscium, SS Piscium and TU Ursae Majoris has been used to estimate their iron abundance, temperature, gravity and absolute magnitude. The stability of the pulsating period is discussed. The nature of SS Psc as a RRc or a HADS is addressed. The reddening of each star is estimated from the Strömgren colour indices and reddening sky maps. The results of three approaches to the determination of [Fe/H], $T_{\rm eff}$ and $\log(g)$ are discussed: Fourier light curve decomposition, the Preston ΔS index and the theoretical grids on the $(b-y)_{\rm o} - c_{1{\rm o}}$ plane.

Key Words: stars: variables: RR Lyrae — techniques: photometry

1. INTRODUCTION

RR Lyrae stars (RRL) are radial pulsators that can be active in the fundamental mode (RRab), first overtone (RRc) or both (RRd). They are common in globular clusters where they populate the horizontal branch (HB). Amplitude and period modulations discovered early in the 20th century (Blažko 1907) have now been identified in a large number of RRab and RRc stars. Perhaps the most prominent of the RRL properties is the correlation between their pulsation period, luminosity and [Fe/H] content: RRL in more metal poor clusters are brighter and have longer periods, the Oosterhoff type II clusters, than in their counterparts Oosterhoff type I (Oosterhoff 1939). The M_V-[Fe/H] relationship has been calibrated by several authors (Chaboyer 1999; Cacciari & Clementini 2003; Arellano Ferro et al. 2008) and confirms the RRL stars as good distance indicators.

Long time series of RRL stars produced by space missions have shown to be very informative on many of the most detailed pulsational properties of these stars, e.g., change of period modes, Blažko periods, period doubling, presence of non-radial modes, etc. An outstanding example is the analysis of *Kepler* space mission data for the star V445 Lyr recently carried out by Guggenberger et al. (2012). CCD time series of globular clusters have also proven very useful in identifying RRL variables and in estimating their physical parameters such as luminosity and metallicity from the Fourier decomposition of their light curves (e.g., Arellano Ferro et al. 2011, and references therein).

Determination of the physical parameters of RRL stars in globular clusters, despite the fact that they are faint, has the advantage that high quality photometry can now be achieved with the use of Differential Imaging Approach techniques (e.g., Alard 2000; Bramich 2008). For the brighter isolated field RRL's long time series are rarer and hence their

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physical parameters and precise position on the HB are more difficult to determine.

Fourier decomposition of light curves of seven field RRL in Bootes and a discussion of their physical parameters from Strömgren photometry was carried out by Peña et al. (2009). Very recently Peña et al. (2012) have published Strömgren data for three RRL's: RU Psc, SS Psc and TU UMa. In the present paper we discuss the use of those data to calculate some physical parameters for these stars.

The paper is organized as follows: In § 2 we describe the data. In § 3 the fundamental characteristics of the three sample stars are presented and the secular period variations are discussed. In § 4 the Fourier light curve decomposition is performed and the implied physical parameters are given. In § 5 we calculate the reddening. In § 6 we present the iron abundance estimation from the Preston ΔS parameter. In § 7 the mean values and pulsating ranges of $T_{\rm eff}$ and $\log(g)$ are estimated by comparison with theoretical grids. In § 8 we summarize our conclusions.

2. DATA

All observations were carried with a multichannel spectrophotometer mounted on the 1.5 m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir (OAN-SPM), Mexico. This spectrophotometer simultaneously observes the Strömgren *uvby* bands and almost simultaneously the two filters that define Hβ (Schuster & Nissen 1988). The observations were obtained on 9 nights between 1989 and 1995 for RU Psc for a total of 310 individual measurements. For SS Psc the observations are from 10 nights spanning from 1992 to 1995 and a total of 139 measurements. For TU UMa the data are from 14 nights between 2004 and 2009 and a total of 50 independent observations.

3. SAMPLE STARS

RU Psc. This is an RRc star with a variable pulsation period that ranges between 0.390318 d and 0.3900421 d according Mendes de Oliveira & Nemec (1988). The period listed by Kholopov et al. (1987) is 0.390385 d. In Figure 1 light and colour curves are phased with the best period found in our data 0.391156 d ± 0.000002 d, which is much larger even than the largest period found by Mendes de Oliveira & Nemec (1988). As has been found by previous authors, the presence of nightly shifts that cannot be taken into account by a single period is clear. A similar behaviour has been seen in double mode RRd stars. Also the cycle-to-cycle variations were attributed to the Blažko effect with a period of about 28.8 d according to Tremko (1964). With an analysis of more than 1100 photometric observations, Mendes de Oliveira & Nemec (1988) concluded that RU Psc is not a double mode or RRd star but that the peculiarities seen in the photometry of RU Psc are due primarily to rapid and irregular period changes, possibly of the Blažko nature, but they also ruled out the presence of a 28.8 d Blažko period.

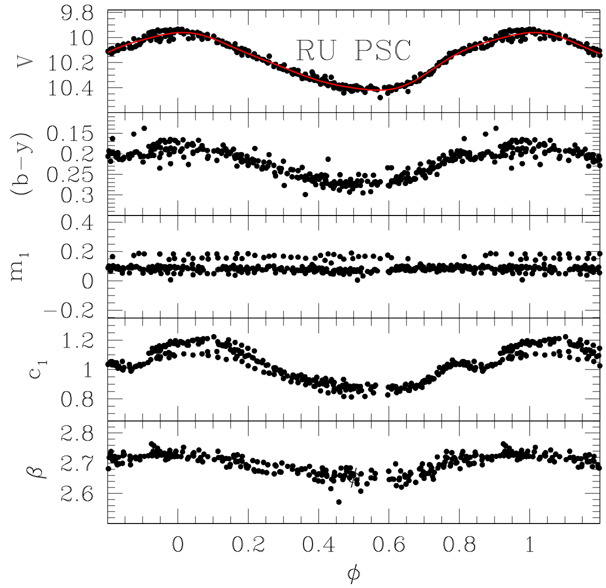

Fig. 1. Light and colour curves of RU Psc phased with the period 0.391156 d. The red line is a fit of the form of equation 2 with four harmonics.

Given the variable nature of the period, probably a more appropriate insight can be found by examining the O-C residuals from a given ephemerides. From our observations we determined two new times of maximum V light at HJD 2447835.6660 d and HJD 2448896.8778 d. In the RRL data base of GEOS[5] (2012) one can find a list of 122 times of maximum spanning from 1924 to 2011. The O-C residuals were calculated with the ephemerides 2440143.40270+0.390385 E of Kholopov et al. (1987) and they are plotted in Figure 2. The errors in the O-C values from photometric or CCD data are better than a few thousands of a day (e.g., Agerer & Hübscher 1996) whereas the visual estimates can reach an uncertainty of about 0.02 d. Thus, the irregular O-C oscilations seen in Figure 2 are real and not a consequence of the uncertainties in the time of maximum estimations. If the time of maximum light deviations about a

[5] http://rr-lyr.ast.obs-mip.fr.

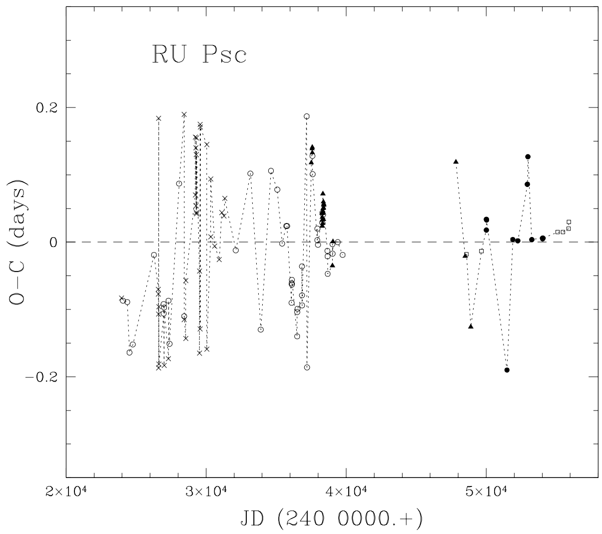

Fig. 2. O-C residuals of RU Psc calculated with the ephemerides 2440143.40270+0.390385 E spanning from 1924 to 2011. Symbols are, open circles: unknown; crosses: photographic; open squares: visual; filled triangles: photoelectric; filled circles: CCD. Error bars for photoelectric and CCD data would be of the size of the symbols while for visual observations they may reach about 0.02 d.

mean are produced by the presence of a secondary oscillation, its frequency should be detected in a period analysis of the residuals, after removing the primary frequency, which is naturally contained in the O-C residuals via the ephemerides. We have used the `period04` programme (Lenz & Breger 2004) to search for periodicities in the residuals. If the star were an RRd, a period of ∼0.527 d would be expected. We found no significant period in the vicinity of the above period, hence we follow Mendes de Oliveira & Nemec (1988) in concluding that RU Psc is not an RRd star. Most recently a group of double mode RRL stars with a period ratio of $P2/P1 \sim 0.61$ have been identified (e.g., Soszyński et al. 2009; Moskalik et al. 2012). This has been interpreted as due to the presence of a non-radial mode. The expected secondary period would be ∼0.238 d which also was not found.

The Blažko nature of RU Psc is controversial. Blažko variations are now well known in a large number of RRc stars (e.g., in M55, Olech et al. 1999; in the LMC, Alcock et al. 2000; in NGC 6362, Olech et al. 2001; in three RRc stars in the OGLE database, Moskalik & Poretti 2003; in Omega Centauri, Moskalik & Olech 2008; in M53, Arellano Ferro et al. 2012) however the light curve of RU Psc differs from most of the known modulated RRc stars in that its modulation is mostly in phase (period) while in amplitude the modulations, if real, are very mild. This suggests that the star undergoes an irregular period variation rather than having a real modulation typical of Blažko variables. The light and colour curves of Figure 1, being formed from data acquired over 6 years, show a dispersion produced by the period irregular fluctuations.

SS Psc. We find this star listed as RRL and as δ Scuti star in different sources. The star is listed as RRc in the GCVS (Kholopov et al. 1987) with a period of 0.28779276 d. Until 1977 it was included in photometric programmes of RRL stars (e.g., Bookmeyer et al. 1977). The star is declared as an RRL in the SIMBAD data base. These facts perhaps led Peña et al. (2012) to include the star in their programme of field RRL *uvby* photometry.

The star was the subject of a *uvby* photometric study of McNamara & Redcorn (1977). These authors concluded, based on its apparently rich metallicity, that the star is not an RRc but a dwarf Cepheid (or RRs) which are considered more massive ($1-2\ M_{\odot}$) post main sequence stars than the less massive ($0.5-0.7\ M_{\odot}$) post giant branch stars.

SS Psc is included in the sample of Antonello et al. (1986) among high amplitude δ Scuti stars (HADS). After Fourier decomposition of the light curves of their sample stars, Antonello et al. (1986) note that among the low harmonic amplitude ratio $R_{21} = A_2/A_1$ stars, SS Psc is indistinguishable from RRc stars, like other HADS, and that on the amplitudes plane A_2 vs A_1 the star seems to lie on a prolongation of the RRc domain toward lower amplitudes. They conclude that SS Psc may be a link between the two classes. The star is included in the list of δ Scuti star of Rodríguez et al. (1994).

The mean gravity calculated by McNamara & Redcorn (1977), 3.29±0.10, is only marginally larger than in RRc stars (∼3.1) and it is based on only 18 photometric data obtained in a single night. Similarly, from its metallicity the star has been estimated as such, due to the rich metallic-line appearance of the spectrum, but to our knowledge no detailed abundance analysis has been performed. In our opinion insufficient arguments have been given to classify SS Psc either as a HADS or as RRc, and a dedicated spectroscopic detailed study is highly desirable. In § 4 we shall further discuss the nature of SS Psc from the Fourier decomposition of the V light curve shown in Figure 3.

Our data for SS Psc include 139 data points in a time span of 1090 days between JD 2448891 and

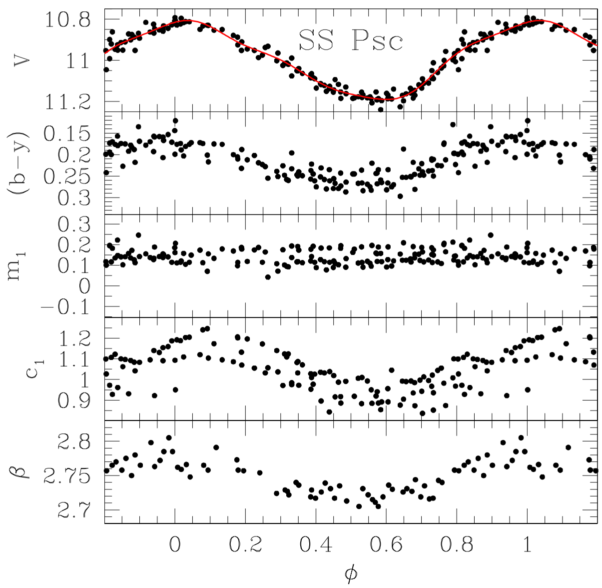

Fig. 3. The light and colour curves phased with the period 0.288712 d. The red solid curve is the fit with four harmonics in equation 2.

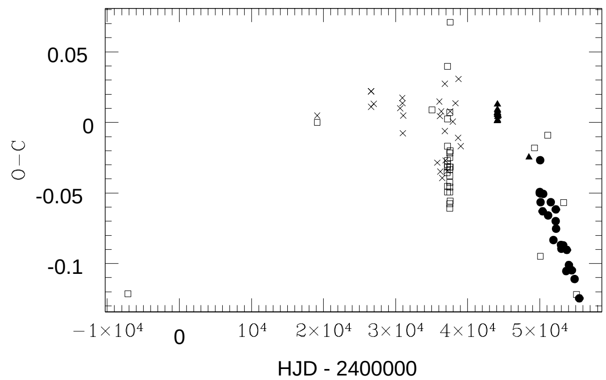

Fig. 4. O-C diagram for the sample of maxima of SS Psc. Symbols are, crosses: photographic; squares: visual; filled triangles: photoelectric; filled circles: CCD. Error bars for photoelectric and CCD data would be of the size of the symbols while for visual observations they may reach about 0.02 d.

2449981. The phasing with Kholopov et al.'s (1987) period of 0.28779276 d gave a small displacements of the maximum light. A Phase Dispersion Minimization (PDM) analysis of our data produced a period of 0.288712 ± 0.000005 d.

In the RRL data base of GEOS (2012) one can find a list of 96 times of maxima and the corresponding O-C diagram built with the ephemerides 2419130.305+0.28779276 E is reproduced in Figure 4. Visual observations show a particularly large scatter at HJD $\sim$ 2443800 which may be due to their larger uncertainty. We have included them for completeness, but if they are ignored the O-C diagram strongly suggests an abrupt period change some time around HJD 2445000. However it could be argued that the O-C is not inconsistent with a secularly decreasing period if older visual observations are considered. In this case, however, the time base would be too short for a clear definition of the period change. We feel that only further observations can disentangle the above possibilities.

TU UMa. This is a RRab star with a V amplitude of about 0.9 mag. and a period of 0.5576587 d (Kholopov et al. 1987). After the work of Szeidl, Olah & Mizser (1986) the star has been well known for undergoing secular period variations and some cyclic variations of the O-C residuals with a period of about 23 years, which led these authors to suggest that the star is in a binary system. Analysis of the times of maximum light have been used by several authors to propose a model which is a combination of a quadratic pulsation ephemerides (a secularly decreasing period) and an orbital timing model which fits the O-C data within the photometry uncertainties (Saha & White 1990; Kiss et al. 1995; Wade et al. 1999).

Wade et al. (1999) also show convincing evidence that the centre-of-mass velocities for TU UMa are consistent with an orbital solution with a period of about 23 yr, an eccentricity of 0.79 and a mass for the companion star of $\sim$0.4 $M_{\odot}$.

While cyclic period variations have been reported in several RRL, the nature of their origin as being caused by multiperiodicity, light time effects or hydromagnetism is still under debate (see Derekas et al. 2004 for a discussion). The continuous observations of both field and cluster RRL stars, the registration of epochs of maximum light and the analysis of line profile variation on high resolution spectra will, however, provide the basis to further interpret the period variations.

A large compilation of times of maximum light is found in the GEOS (2012) data base. We have noticed that this compilation misses 33 of the 41 times of maximum listed in Table 2 of Wade et al. (1999). In Figure 5 we present the complete O-C residuals, which for a direct comparison with the models of Wade et al. (1999), were calculated with the ephemerides used by these authors 2425760.4364+0.557658109 E, supplemented with the time of maximum HJD 2454552.90345 calculated in this work.

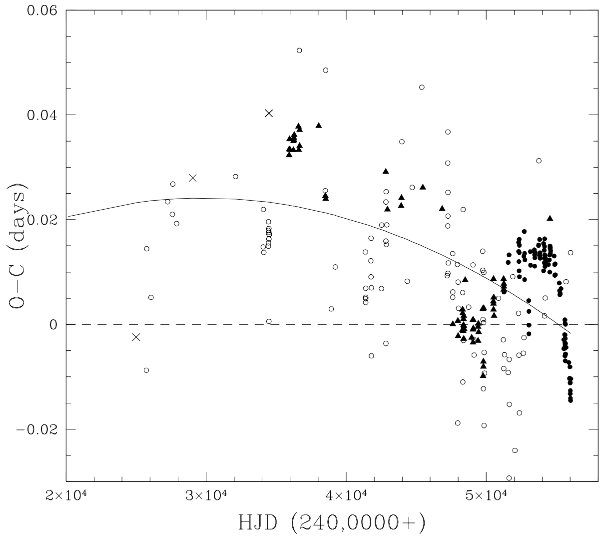

Fig. 5. O-C diagram for the sample of maxima of TU UMa. Symbol are, crosses: photographic; open circles: visual; filled triangles: photoelectric; filled circles: CCD. The O-C uncertainties are as in Figures 2 and 4. The black solid curve is the parabolic fit to all data.

The O-C diagram clearly shows the secular variation of the pulsating period which can be represented by

$$\mathrm{O} - \mathrm{C} = 0.02351 + 1.71274 \times 10^{-7}\ \mathrm{E} - 1.17113 \times 10^{-11}\ \mathrm{E}^2, \qquad (1)$$

this implies a period decreasing rate of -1.3 ms yr^{-1}. Other determinations range from -9.9 ms yr^{-1} (Kiss et al. 1995) to -1.7 ms yr^{-1} (for some models of Wade et al. 1999). Since the model calculation by Wade et al. (1999) numerous new O-C are available, mostly from CCD measurements. Inclusion of these data in the O-C diagram (Figure 5 for HJD $\geq$ 2451545.) neatly delineates another 'orbital loop'. We feel it is worth waiting for another ten years of accurate times of maximum light registration before the orbit is accurately solved.

Our data consist of 50 data points obtained between JD 2453102 and 2454881. Figure 6 shows the light and colour curves phased with the period of Kholopov et al. (1987), which we shall use for the Fourier decomposition.

4. FOURIER ANALYSIS

Given the light curves of the RRL stars we make an attempt to estimate their iron abundance, effective temperature and absolute magnitude using the Fourier light curve decomposition approach. For SS Psc, given its unclear nature as an RRL (see § 3

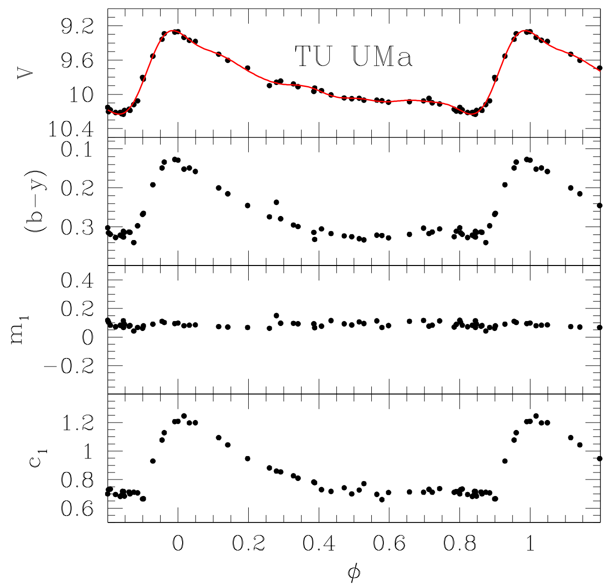

Fig. 6. Light and colour curves of TU UMa phased with the ephemerides 2454552.90345+0.5576587 E. The red solid curve is the fit with nine harmonics in equation 2. Hβ data are not available in Peña et al. (2012) for this star.

and further below in this section for a discussion), we shall not apply this approach since the involved calibrations may not be applicable.

The light curve of a periodic variable can be represented by an equation of the form:

$$m(t) = A_0 + \sum_{k=1}^{N} A_k \cos(\frac{2\pi}{P} k(t-E) + \phi_k),$$

and the phase and amplitude ratio Fourier parameters are defined as $\phi_{ij} = j\phi_i - i\phi_j$ and $R_{ij} = A_i/A_j$.

Decomposing the light curve in its harmonics has proved to be useful in estimating physical parameters in field RRL stars (e.g., Peña et al. 2009) and in globular clusters (e.g., Arellano Ferro et al. 2011, and references therein), through the use of semi-empirical relationships (e.g., Jurcsik & Kovács 1996; Morgan, Wahl, & Wieckhorts 2007).

Epochs and periods used in the application of equation 2 and the resulting amplitudes A_i and phases ϕ_{ij} for each harmonic for the three sample stars are reported in Table 1.

For the RRab star, TU UMa, we used the calibration of Jurcsik & Kovács (1996):

$$[\mathrm{Fe/H}]_{\mathrm{J}} = -5.038 - 5.394\ P + 1.345\ \phi_{31}^{(s)}, \qquad (2)$$

The standard deviation of this calibration is 0.14 dex (Jurcsik 1998) and delivers $[\mathrm{Fe/H}]_{\mathrm{J}}$ in

TABLE 1

FOURIER COEFFICIENTS DERIVED FROM THE FIT

ID	E_0 2400000.0+	P (days)	A_0	A_1	A_2	A_3	A_4	ϕ_{21}	ϕ_{31}	ϕ_{41}	N
RU Psc	47835.6687	0.391156	10.192	0.224	0.020	0.009	0.010	4.553	4.518	2.757	4
			0.001	0.002	0.002	0.002	0.002	0.084	0.178	0.171	
SS Psc	49980.7713	0.288712	11.001	0.181	0.020	0.006	0.010	4.972	5.100	3.025	4
			0.002	0.003	0.003	0.003	0.003	0.155	0.499	0.309	
TU UMa	54552.9035	0.5576587	9.857	0.328	0.164	0.115	0.071	3.893	8.150	6.265	7
			0.005	0.007	0.007	0.007	0.007	0.060	0.090	0.130	

TABLE 2

FOURIER DECOMPOSITION PHYSICAL PARAMETERS FOR TWO RR LYRAE STARS

ID	$[Fe/H]_{ZW}$	$\log(T_{\rm eff})$	M_V	$\log(L/L_\odot)$	μ_0	distance (pc)
RU Psc	-1.62 ± 0.14	3.859 ± 0.003	0.51 ± 0.04	1.724	9.65 ± 0.04	851 ± 16
TU UMa	-1.53 ± 0.14	3.809 ± 0.003	0.60 ± 0.04	1.672	9.25 ± 0.04	710 ± 15

a scale that can be transformed into the Zinn & West (1984) scale $[Fe/H]_{ZW}$ through the relationship $[Fe/H]_J = 1.43\ [Fe/H]_{ZW} + 0.88$ (Jurcsik 1995). The above equation can be used if the light curve satisfies the *compatibility parameter* D_m which should be smaller than 3.0 (Jurcsik & Kovács 1996). For TU UMa we calculated $D_m = 2.1$.

The effective temperature was estimated from the calibrations of Jurcsik (1998)

$$\log(T_{\rm eff}) = 3.9291 - 0.1112\ (V-K)_{\rm o} - 0.0032\ [{\rm Fe/H}], \quad (3)$$

with

$$(V-K)_{\rm o} = 1.585 + 1.257\ P - 0.273\ A_1 - 0.234\ \phi_{31}^{(s)} + 0.062\ \phi_{41}^{(s)}. \quad (4)$$

Equation (3) has a standard deviation of 0.0018 (Jurcsik 1998), but the accuracy of $\log(T_{\rm eff})$ is mostly set by the colour equation (4). The error estimate on $\log(T_{\rm eff})$ is 0.003 (Jurcsik 1998).

The value of the absolute magnitude comes from the calibration of Kovács & Walker (2001):

$$M_V(K) = -1.876\ \log(P) - 1.158\ A_1 + 0.821\ A_3 + K, \quad (5)$$

which has an standard deviation of 0.04 mag. The value of $K = 0.41$ was adopted to scale the luminosities of RRab stars with the distance modulus of 18.5 for the Large Magellanic Cloud (LMC) (see the discussion in Arellano Ferro, Giridhar, & Bramich 2010, in their § 4.2).

For the RRc star RU Psc we calculated $[Fe/H]_{ZW}$ from the calibration of Morgan et al. (2007):

$$[{\rm Fe/H}]_{ZW} = 52.466P^2 - 30.075P + 0.131(\phi_{31}^{(c)})^2 + 0.982\phi_{31}^{(c)} - 4.198\phi_{31}^{(c)}P + 2.424. \quad (6)$$

This calibration provides iron abundances with a standard deviation of 0.14 dex. $T_{\rm eff}$ comes from the calibration of Simon & Clement (1993):

$$\log(T_{\rm eff}) = 3.7746 - 0.1452\ \log(P) + 0.0056\ \phi_{31}^{(c)}, \quad (7)$$

and M_V is obtained from the calibration of Kovács (1998):

$$M_V(K) = -0.961\ P - 0.044\ \phi_{21}^{(s)} + 4.447\ A_4 + 1.061, \quad (8)$$

with an error of 0.042 mag.

Following Cacciari et al. (2005), we have used equation 8 with the zero point 1.061 in order to bring the absolute magnitudes in agreement with the mean magnitude for the RRL stars in the LMC, $V_0 = 19.064 \pm 0.064$ (Clementini et al. 2003).

The results obtained from this analysis are compiled in Table 2. The absolute magnitude M_V was converted into $\log(L/L_\odot)$ using $M_{{\rm bol}\odot} = +4.75$ and the colour excesses given in § 5.

At this point it is worth mentioning that, although calibrations exist to estimate the stellar mass from the Fourier parameters for the RRc (Simon & Clement 1993) and the RRab (Jurcsik 1998) stars,

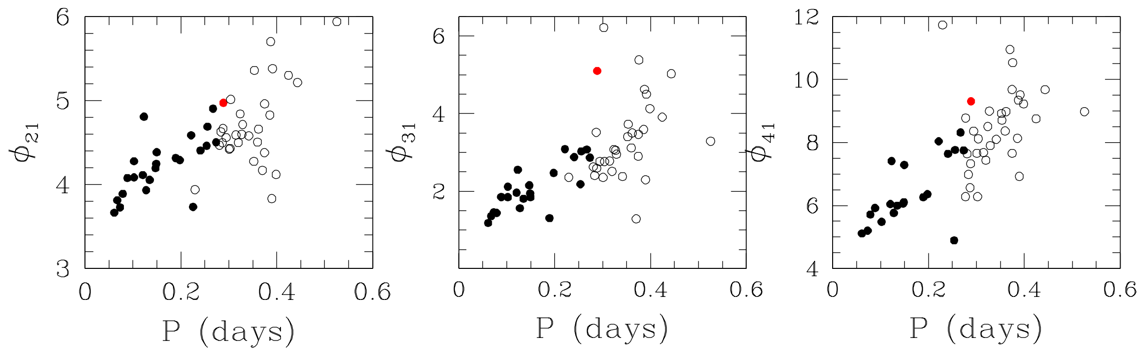

Fig. 7. Phases ϕ_{21}, ϕ_{31} and ϕ_{41} as function of period for a sample of HADS and HASXP (filled circles) and for some RRc stars in globular clusters (open circles). The red point represents SS Psc. See text for discussion.

Cacciari, Corwin, & Carney (2005) have shown that the results are unreliable, and therefore we have refrained from using such calculations.

The case of SS Psc is worth a separate comment. The coverage and density of the V light curve of Figure 3 allow the Fourier decomposition in four harmonics with the amplitudes and phases listed in Table 1. Given its unclear classification as a HADS or as a RRc, in Figure 7 we plotted its Fourier phases ϕ_{21}, ϕ_{31} and ϕ_{41} as a function of period for a sample of HADS and HASXP stars taken from the paper of Antonello et al. (1986) and a sample of RRc stars in globular clusters taken from several papers published by our group (Arellano Ferro et al. 2004, 2008, 2011; Bramich et al. 2011; Kains et al. 2012; Lázaro et al. 2006). Its ϕ_{21} and ϕ_{41} phases indicate that SS Psc tends to mix better with the RRc stars than with the HADS and that ϕ_{31} is peculiarly large. Hence its [Fe/H] and $T_{\rm eff}$ from equations 6 and 7 would be peculiar and not reliable as for an standard RRc, thus we do not report here the values. While these arguments seem to rule out SS Psc as a HADS they indicate that star remains as peculiar among the RRc star.

5. REDDENING

The determination of the reddening in field stars is complex. However, a good estimation can be obtained from the maps of Galactic dust reddening and extinction of Schlegel, Finkbeiner, & Davis (1998). These maps give values of $E(B-V)$ of 0.047, 0.051, 0.023 in the directions of RU Psc, SS Psc and TU UMa respectively, which correspond to values of $E(b-y)$ 0.034, 0.037 and 0.016.

From $uvby-\beta$ photometry for F type dwarfs and giants one could also use the calibration of Crawford (1975). We have calculated the magnitude-weighted means of $b-y$, m_1, c_1 and β from the colour curves in Figures 1, 3 and 6. For TU UMa there are no β measurements, thus for this star we used the mean values of Hauck & Mermilliod (1998). SS Psc and TU UMa lie a bit beyond the validity of the calibration (β is too large), and the calculation implied some extrapolation. TU UMa correctly fits in the calibration ranges. We found $E(b-y) = 0.014$, 0.044 and -0.006 for RU Psc, SS Psc and TU UMa respectively. Using their own photometry and the same calibration, McNamara & Redcorn (1977) calculated $E(b-y) = 0.016$ for SS Psc.

Based on the above calculations we adopted $E(b-y)$ as 0.01, 0.04 and 0.00 for RU Psc, SS Psc and TU UMa respectively.

6. [Fe/H] FROM THE ΔS PARAMETER

It is of interest to compare the values of [Fe/H] calculated from the Fourier decomposition approach with the estimation via the ΔS metallicity parameter defined by Preston (1959) as $\Delta S = 10$ [Sp(H)-Sp(CaII)] that is, the difference between the hydrogen and K-line types in units of tenths of a spectral class. Average values of ΔS for the three stars in our sample are reported by Suntzeff et al. (1994) as 7.65 ± 1.77 for RU Psc, 2.95 ± 1.34 for SS Psc and 6.10 ± 1.83 for TU UMa. Suntzeff et al. (1994) also provide the following empirical relations [Fe/H] $= -0.155\Delta S - 0.425$ for RRc stars and [Fe/H] $= -0.158\Delta S - 0.408$ for RRab stars. Hence the corresponding values of [Fe/H] are -1.61 ± 0.27, -0.88 ± 0.21, and -1.37 ± 0.29 for RU Psc, SS Psc and TU UMa respectively. The above ΔS values and their corresponding iron abundances are summarized in Table 3. For TU UMa Layden (1994) compiles three values of ΔS from the literature that average 6.9 and then [Fe/H]=-1.50.

If the calibration of Fernley et al. (1997) is preferred, [Fe/H] $= -0.195\Delta S - 0.13$, then the [Fe/H]

TABLE 3

ΔS FOR THE SAMPLE STARS

ID	Bayley's type	Spectral type	ΔS[1]	[Fe/H](ΔS)
RU Psc	RRc	A7-F3	7.65 ± 1.77	-1.61 ± 0.27
SS Psc		A7-F2	2.95 ± 1.34	-0.88 ± 0.21
TU UMa	RRab	F2	6.10 ± 1.83	-1.37 ± 0.29

[1]Suntzeff, Kraft, & Kinman (1994).

TABLE 4

[Fe/H], $T_{\rm eff}$ AND log(g) DETERMINATIONS FOR THE SAMPLE STARS

ID	[Fe/H]$_{\rm ZW}$	[Fe/H](ΔS)	[M/H] Adopted	$T_{\rm eff}$ Fourier	$T_{\rm eff}$ range	log(g) range
RU Psc	−1.62	−1.61	−1.5	7229	6200–6800	2.2–2.7
SS Psc		−0.88	−1.0		6500–7500	2.5–3.2
TU UMa	−1.53	−1.37	−1.5	6437	5700–7200	2.2–2.9

values are -1.62 ± 0.27, -0.45 ± 0.21 and -1.32 ± 0.29 for RU Psc, SS Psc and TU UMa respectively. For RU Psc and TU UMa the [Fe/H] values reported by Fernley et al. (1998) are -1.75 ± 0.15 and -1.51 ± 0.15. These values were calculated from the ΔS parameter and the relation $[{\rm Fe/H}] = -0.195\Delta S - 0.13$. The small differences in [Fe/H] are due to the use of slightly different values of ΔS.

Therefore, the agreement between the [Fe/H] values from the Fourier light curve decomposition (Table 4) and the spectroscopic estimates from the ΔS parameter for RU Psc and TU UMa is, within the uncertainties, very good.

The ΔS for SS Psc indicates that the star is much more metal rich than the RRL stars RU Psc and TU UMa and confirms the comments of McNamara & Redcorn (1977) that the star is metal-strong as its spectrum is rich of metallic lines and its m_1 index is large. The mean m_1 index in our data for SS Psc (0.142) is in fact larger than in RU Psc (0.091) and TU UMa (0.088), consistent with its higher metallicity.

7. $T_{\rm eff}$ AND log(g) FROM THEORETICAL GRIDS

Once the reddening has been inferred, and taking advantage of the simultaneity in the acquisition of the data in the different colour indices, we have plotted our data on the $(b-y)_{\rm o}$ - $c_{1{\rm o}}$ plane along with the theoretical grids calculated by Lester, Gray, & Kurucz (1986). The $(b-y)_{\rm o}$ - $c_{1{\rm o}}$ plane was chosen because loci of different values of $T_{\rm eff}$ and log(g) are clearly separated. This would provide good estimates of the mean $T_{\rm eff}$ and log(g) and the range of variation along the pulsation cycle. The grids are available for a large range of chemical compositions. For each star we selected the grid with an [Fe/H] value close to the corresponding [Fe/H]$_{\rm ZW}$ and [Fe/H](ΔS) values in Table 4.

The $(b-y)_{\rm o}$ - $c_{1{\rm o}}$ planes for RU Psc, SS Psc and TU UMa are presented in Figure 8, and the mean $T_{\rm eff}$ and log(g) and their ranges are given in Table 4. It is interesting to note that SS Psc, which seems not to be a standard RRc star, but rather a post main sequence star, probably a dwarf Cepheid (McNamara & Redcorn 1977) or HADS (Antonello et al. 1986), is indeed much more metal rich than its RRL counterparts, and the gravity range is slightly larger than for the two RRL stars, between 2.5 and 3.2. SS Psc also seems to be hotter than the two RRL stars by about 500 K.

8. SUMMARY AND CONCLUSIONS

From $uvby-\beta$ data collected in several campaigns reported by Peña et al. (2012) we have addressed the secular variations of the pulsation period of the RRc star RU Psc, the RRab star TU UMa and the probable RRc star SS Psc. The data sets for each star span between 3 and 6 years and have been used to provide a few new times of maximum light. In

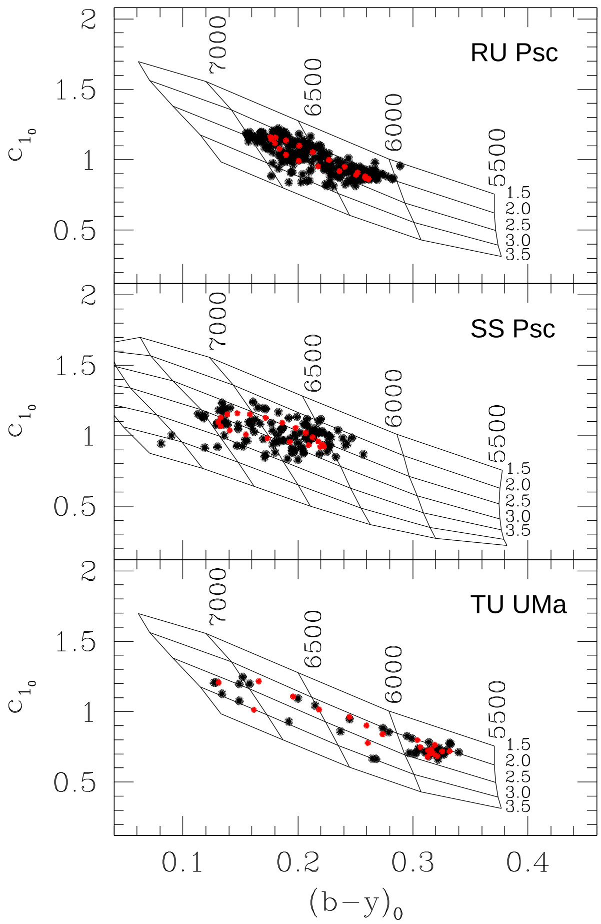

Fig. 8. Variation of RU Psc, SS Psc and TU UMa on the $(b-y)_\mathrm{o}$ - $c_{1\mathrm{o}}$ plane along with the theoretical grids for [M/H] of −1.5, −1.0 and −1.5, respectively, from Lester et al. (1986). Nearly vertical curves are of constant T_{eff}, while nearly horizontal curves are for constant $\log(g)$. Black circles are individual observations. Red circles show the loop described by the cycle colour variations calculated by Fourier decomposition of the colour curves.

all cases the data fully covered the pulsation cycle and allow the use of the Fourier approach and the loop on the $(b-y)_\mathrm{o}$ - $c_{1\mathrm{o}}$ to calculate [Fe/H], T_{eff} and $\log(g)$.

The three sample stars are subject to secular period instabilities. In the case of RU Psc a systematic period change cannot be seen, but rather an apparently irregular period oscillation which causes the observed dispersion in the maxima of the light curve produced by a data set obtained over 6 years. We found no traces of a significant secondary period and conclude that the star is not an RRd or double mode pulsator. For SS Psc the O-C diagram strongly suggests an abrupt period change some time around JD 244 5000 but it can also be argued that the residuals are not inconsistent with a secularly decreasing period. TU UMa exhibits a complex O-C diagram that has been interpreted by several authors as being produced by a secular pulsation period change of the RRL star plus the light time effects in a binary system. The inclusion of the last ten years of times of maximum clearly define the orbital effect.

The reddening in the direction of each sample star has been estimated from the reddening sky maps of Schlegel et al. (1998). Then, when possible, we used the colours m_1, c_1 and β in the calibrations of Crawford (1975) to calculate $E(b-y)$. Guided by these results and considering the uncertainties we adopted what seemed to be 'bona fide' reasonable estimates of $E(B-V)$.

The physical parameters found in this work for the sample stars are summarized in Table 4. For the two RRL stars RU Psc and TU UMa the [Fe/H] value obtained from the Fourier and the ΔS index methods agree within the uncertainties. The ranges of T_{eff} and $\log(g)$ from the $(b-y)_\mathrm{o}$ - $c_{1\mathrm{o}}$ colour distribution bracket well the Fourier value for TU UMa while for RU Psc the Fourier value is towards the higher limit. The gravity ranges for the three stars are consistent with values for stars in or near the HB.

SS Psc is much more metal rich than the RRL stars RU Psc and TU UMa, as is indicated by the several metallicity tracers such as the ΔS and the mean m_1 indices given in this paper and the richness of metallic lines in its spectrum noticed by McNamara & Redcorn (1977). The gravity estimated by these authors, 3.29, is a bit larger than the range along the pulsation cycle estimated in the present work (2.5–3.2) despite the slightly larger value of $E(b-y)$ adopted here. Both the metallicity and gravity are comparable to those in other well-established RRL stars. However, its Fourier ϕ_{31} highlights the star as peculiar among RRc stars in globular clusters. In our opinion it is not possible to completely rule out the RRL nature of SS Psc with the information available at present.

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