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Radial velocities and iron abundances of field RR Lyraes. II.

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Abstract. This is the second of the papers devoted to derive radial velocities and iron abundances of field RR Lyraes observed by HIPPARCOS. Our abundances show good agreement with those in the literature obtained both from photometric (ΔS index) and spectroscopic methods. Binary candidates and stars misclassified as RR Lyraes in the original HIPPARCOS list have been also identified.[1]

Key words: stars: variables — stars: abundances — stars: kinematics

1. Introduction

In this paper we present the radial velocities and iron abundances for field RR Lyraes observed by the HIPPARCOS satellite. By combining these data with the proper motions and V magnitudes from HIPPARCOS it will be possible to determine the RR Lyrae absolute magnitude–metallicity relation using the method of Statistical Parallax (e.g. Hawley et al. 1986; Strugnell et al. 1986). In an earlier paper (Fernley & Barnes 1997, hereafter Paper I), systemic velocities and iron abundances were presented for 56 RR Lyraes using echelle spectra taken at McDonald Observatory, Texas. In this paper we present similar data for a further 45 RR Lyraes observed at either Calar Alto Observatory, Spain or Sutherland Observatory, S. Africa.

2. Observations and data reduction

The observations were performed in different observing runs carried out in 1994–1995 at two observatories: the Observatorio de Calar Alto (Almería, Spain) and the Sutherland Observatory (South Africa). Observations at Calar Alto were made in May and December 1994 using the Coudé spectrograph on the 2.2 m telescope. The wavelength covers ≈ 230 Å (4 160 Å – 4 390 Å). The resolving power was 22 000 which corresponds to a reciprocal spectral dispersion of 0.20 Å/pixel at Hγ. Observations at Sutherland were made in July 1995 using the Image Tube Spectrograph and the RPCS detector on the 1.9 m telescope. The spectra cover the wavelength range 4 070 Å – 4 490 Å. The resolving power was 19 000 which corresponds to a reciprocal spectral dispersion of 0.23 Å/pixel.

The exposure times in all the runs were limited to 15 minutes for the RR Lyraes in order to prevent "phase blurring". In general, three spectra were obtained for each RR Lyrae. The first spectrum was arbitrarily assigned as phase zero and then, using the published periods from the GCVS, two further spectra were obtained separated by plus or minus a third of a cycle from the first spectrum.

The spectra were reduced using the FIGARO reduction package: the raw spectra were bias-subtracted, flatfield-corrected (two or more master flatfield exposure were taken every night) and background-subtracted before the spectral extraction. The wavelength calibration of the stellar spectra was done with thorium-argon comparison spectra. Because of the variations in the velocity zero point of the Image Tube Spectrograph at Sutherland (probably due to a mechanical slippage of the grating mount), arcs were taken before and after every observation. In the Calar Alto runs, arcs were taken at the beginning and the end of every night. Polynomial calibrations of wavelength as a function of pixel number were calculated for each comparison spectrum. A fourth order polynomial fit was used for Sutherland spectra whereas a second order polynomial fit was found adequate for the Calar Alto sample. In both cases a precision better than 0.04 Å was achieved which corresponds to ≈ 2.8 km s^{-1} at 4 200 Å. The continuum

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[1] Appendix is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u- strasbg.fr/Abstract.html

windows were chosen with the aid of the *Atlas of Procyon* (Griffin & Griffin 1979) and the continuum level calculated by fitting a second-degree polynomial. The normalized spectra were then derived by dividing the extracted spectra by this continuum level. The signal-to-noise ratio of the spectra varied between 5 and 25 depending on the magnitude of the star and the quality of the seeing. In addition, several IAU radial velocity standard stars were observed each night to measure the zero-point offset in radial velocity of our measurements.

3. Radial velocities

A cross-correlation technique was used to calculate the radial velocities of the observed RR Lyrae. As a first step, the original wavelength range was logarithmically rebinned from 4 189.4 to 4 389.4 Å for Calar Alto spectra and from 4 073.6 to 4 446.7 Å for Sutherland spectra to 1 024 and 2 048 data points respectively. After this, the spectra were cross-correlated (using a Fast Fourier Transform technique) against the observed IAU radial velocity standards (Table 1). A 5% cosine-bell was used to remove the start and end spectrum discontinuities. The cross-correlation peak was then fitted to a parabola, the maximum value of the parabola being the radial velocity difference between the standard and the target star. Finally, the heliocentric correction was applied using the standard IRAF package.

The phases of our observations were calculated using the published periods from the GCVS and an arbitrary zero-point. Systemic velocities were then determined by fitting these phased radial velocity measurements for each star to the "standard" RRab Lyrae radial velocity curve given by Liu (1991). A free parameter in the Liu curve is the amplitude. Liu found 22 RRab Lyraes with published radial velocity curves and these have a mean amplitude of 61.5 km s^{-1} with an rms scatter of 8.4 km s^{-1}. Liu shows that there is a correlation between light curve amplitude and velocity amplitude; however, since the light curve amplitude is not known for many of the stars in our sample, we have used the mean amplitude of 61.5 km s^{-1} to construct the "standard" curve. Amongst the stars for which we have three well-phased spectra with good S/N there are 4 RRab Lyraes and 2 RRc Lyraes with complete radial velocity curves available in the literature. Comparing our values of the systemic velocity with the literature values for the 4 RRab Lyraes showed a mean difference of 1.7 km s^{-1} and an rms difference of 3.1 km s^{-1}. For the RRc Lyraes, where the velocity amplitude is smaller and the velocity curve more symmetric, we determined the systemic velocity by simply taking a mean of our three measurements. Again, comparing our systemic velocities with the literature values showed, for the two RRc Lyraes, a mean difference of 1.5 km s^{-1} and an rms difference of 2.1 km s^{-1}.

Thus for those stars where we have three well-phased radial velocities and good S/N spectra, a realistic $1-\sigma$ error in the systemic velocity is ± 3 km s^{-1}. For those stars with fewer measurements and/or lower S/N the errors are larger. The full list of RR Lyraes, their systemic velocities and associated errors is given in the Appendix (available electronically).

Table 1. IAU radial velocity standards

Identification	Velocity (km s^{-1})
HR 0033	14.7
HR 1101	27.9
HD 65934	35.0
HR 4540	5.0
HR 5694	53.5
HR 7560	0.1
HR 8969	5.3

3.1. Binary candidates

Because the Horizontal Branch is a relatively short-lived phase of stellar evolution, most companion stars will be much fainter than the RR Lyrae itself, i.e. the companions will either be low-mass main sequence stars or white dwarfs. In general, therefore, the only methods available to detect companions are to look for variations in either the time of maximum light or the systemic velocity. In Table 2 we list those RR Lyraes which show significant differences between our values and previous values of the systemic velocity. Examination of the spectra of these stars showed no evidence of line doubling for any of them.

The only one of stars included in Table 2 previous suspected to be a member of a binary is TU UMa. Saha & White (1990), using published times of maximum light, calculated the orbital parameters for TU UMa and our value of the systemic velocity is not inconsistent with their prediction. For the other stars, a literature search showed there were insufficient published times of maximum light to attempt an orbital solution and clearly it would be of value to place these stars in a long-term observing programme in order to acquire these data.

4. Effective temperatures and metallic abundances

It is well established that the Balmer lines are good temperature indicators for $T_{\rm eff} \leq 8\,500$ K because of their small gravity and metallicity dependence (Smalley & Dworetsky 1993; Furhmann et al. 1994). In this work, effective temperatures for both non-variable and RR Lyrae stars have been obtained from the comparison, using a least-squares fitting technique, between the observed Hγ

Table 2. Binary candidates

Identification	Systemic velocity		Ref. (see Appendix)
	This work (km s^{-1})	Previous work (km s^{-1})	
TY Aps	90±3	129 ± 14, 60 ± 16	9, 17
BX Dra	−24±3	75 ± 30	9
XX Hya	32±30	52 ± 24, −10 ± 35, 95 ± 10	9, 14, 16
BX Leo	−7±15	27 ± 5	16
CN Lyr	13±20	67 ± 30, 27 ± 5	9, 16
TU UMa	96±3	84 ± 2, 90 ± 2	1, 8
		77 ± 2, 101 ± 5	12, 16

Table 3. Effective temperatures, surface gravities and [Fe/H] abundances of the non-variable stars. The number in parenthesis indicates the number of lines used in the abundance determination

Identification	Eff. Temp (K)	Previous work	[Fe/H]	Previous work	log g
HR 0033	6279	6204[1]/6156[7]	−0.12(8)	−0.38[1]/−0.40[7]	4.07[1]/4.12[7]
HR 0033	6254		−0.21(9)		
HR 0033	6346		−0.27(7)		
HR 2943	6542	6500 − 6750[12]	−0.07(5)	0.00[12]	4.00[12]
HR 4540	6062	6095[3]/6120[2]/6176[1]	+0.08(5)	0.13[2]/0.13[1]	4.22[2]/4.14[1]
HR 4540	6060		+0.16(5)		
HR 4540	5973		−0.04(6)		
HR 4540	6095		+0.09(5)		
HR 5694	6204	6142[6]/6055[8]	+0.05(10)	−0.12[8]	
HR 5694	6278		−0.11(8)		
HR 5694	6102		+0.02(7)		
HR 5694	6113		+0.04(7)		
HR 5694	6258		+0.06(6)		
HR 5694	6140		+0.00(6)		
HR 5694	5950		−0.16(6)		
HR 7560	6273	6146[1]/6360[4]	+0.00(7)	0.09[1]/0.18[5]	4. 14[1]/4.40[5]
HR 7560	6231		+0.15(7)		
HR 7560	6190		−0.10(5)		
HR 7560	6188		+0.19(6)		
HR 7560	6132		+0.13(6)		
HR 7560	6060		+0.08(6)		
HR 8969	6318	6255[1]/6157[7]/6105[9]	−0.19(9)	−0.17[1]/−0.21[7]	4.16[1]/4.17[9]
HR 8969	6205		−0.06(8)		
HR 8969	6184		−0.15(5)		
HR 8969	5991		−0.19(6)		
HR 8969	6021		−0.15(6)		
HR 8969	6258		−0.11(6)		
SAO 37362	6133	6132[3]/6212[10]/6205[11]	+0.07(3)	0.0[3]/0. 09[10]/−0.16[11]	4.0[3,12]/4.17[10]
SAO 101826	6306	6220[2]/6233[3]/6333[1]	−0.23(6)	−0.32[2]/ −0.16[1]	4.24[2]/4.25[3]

1: Edvardsson et al. (1993); **2:** Bell et al. (1994); **3:** Alonso et al. (1996); **4:** Sokolov (1995); **5:** Borges et al. (1995); **6:** Cayrel de Strobel et al. (1992); **7:** King & Boesgaard (1995); **8**: Carney et al. (1987); **9:** Favata et al. (1996); **10:** Tomkin et al. (1995); **11:** Blackwell et al. (1994); **12:** Drake & Laming (1995).

Table 4. Adopted parameters and derived quantities for the RR Lyrae stars observed at Calar Alto. The number in parenthesis indicates the number of lines used in the abundance calculation

Identification	Ephemeris	Phase	$T_{\rm eff}$ (K)	[Fe/H]
AT And	42343.420+0.616915[2]	0.09	6690	−1.14 (1)
SW And	47116.185+0.442266[3]	0.86	5921	−0.36 (6)
AE Boo	30388.203+0.314892[2]	0.20	6616	−0.95 (4)
AE Boo		0.59	6296	−1.18 (3)
AE Boo		0.28	6978	−0.99 (3)
AE Boo		0.94	6796	−0.96 (3)
RS Boo	46948.720+0.377337[1]	0.47	6233	−0.31 (4)
RS Boo		0.87	6210	−0.34 (4)
RR Cet	46773.724+0.553038[1]	0.65	6000	−1.24 (2)
SU Dra	46833.664+0.66042[1]	0.67	5721	−1.97 (5)
SU Dra		0.99	7200	−1.42 (2)
SW Dra	46495.754+0.569669[1]	0.30	6190	−0.70 (4)
SW Dra		0.00	7279	−0.84 (2)
XX Hya	39832.011+0.507741[2]	0.40	6839	−1.22 (2)
TT Lyn	46773.679+0.597436[1]	0.74	5888	−1.27 (2)
TT Lyn		0.41	6223	−1.38 (4)
CN Lyr	44486.334+0.411382[2]	0.09	6582	−0.09 (2)
CN Lyr		0.40	6173	−0.10 (2)
KX Lyr	39630.870+0.440904[2]	0.20	6368	−0.30 (1)
KX Lyr		0.46	6248	−0.41 (3)
DH Peg	44463.571+0.255510[2]	0.26	7285	−1.35 (1)
DZ Peg	33891.308+0.607344[2]	0.41	6400	−1.21 (3)
VZ Peg	38317.293+0.306486[2]	0.54	7010	−1.63 (3)
AR Per	46773.473+0.425549[1]	0.24	6560	−0.23 (2)
AR Per		0.48	6143	−0.23 (3)
AP Ser			6475	−1.62 (3)
VY Ser	38466.244+0.714096[1]	0.24	6101	−1.46 (2)
VY Ser		0.62	5869	−1.42 (2)
T Sex	46833.592+0.324712[3]	0.32	6650	−1.30 (3)
T Sex		0.62	7200	−1.27 (2)
T Sex		0.32	6737	−1.25 (2)
SX Uma			6563	−1.75 (1)
SX Uma			7342	−1.51 (1)

1: Fernley & Barnes (1996); **2:** Kholopov et al. (1990); **3:** Liu & Janes (1990).

profile and a grid of synthetic profiles using ATLAS8 (Kurucz 1979). The gravity and metallicity were fixed to $\log g = 2.75$ and $[M/H] = -1.0$ for the RR Lyrae stars and to $\log g = 4.0$ and $[M/H] = 0.0$ for the sample of non-variable stars. Effective temperatures of the observed stars are given in Tables 3, 4 and 5.

It has been pointed out that for stars cooler than 8 500 K, convection is starting to become efficient enough to modify the temperature gradient and hence the Balmer profiles with the exception of Hα (van't Veer–Menneret & Megessier 1996). However, we have not found any evidence for this. Comparing our effective temperatures derived from Hγ and those obtained from the literature for the non-variable stars shows a mean difference and a standard deviation of -11 ± 73 K. Moreover, previous comparisons between effective temperatures derived from Hβ from the Infrared Flux method and spectrophotometric methods (Solano & Fernley 1997) did not show systematic differences either.

The crowding of the observed spectral region made the line selection difficult and only a small number of Fe I lines were selected for the abundance calculation (Table 6): weak lines (with associated large errors due to the moderate S/N ratio of our observations) and strong lines (sensitive to saturation effects) were not considered. The relatively low signal-to-noise together with the crowded spectral region also cause an uncertainty in the measured equivalent width. An estimation of this uncertainty was obtained by comparing the equivalent widths of lines of non-variable stars with two or more observations. This gave a typical error of 7%. For the RR Lyrae stars, which

Table 5. Same as Table 4 but for Sutherland observations

Identification	Ephemeris	Phase	$T_{\rm eff}$ (K)	[Fe/H]
TY Aps	39726.275+0.501693[1]	0.16	7131	−0.66 (5)
TY Aps		0.39	6194	−0.92 (4)
XZ Aps	28715.330+0.587434[1]	0.93	6579	−0.55 (8)
BV Aqr	37524.218+0.364048[1]	0.62	7011	−1.16 (3)
BV Aqr		0.09	6868	−1.22 (3)
BV Aqr		0.43	6394	−1.20 (5)
BV Aqr		0.94	7138	−1.15 (1)
RR Cet	46773.724+0.553038[3]	0.77	6044	−1.29 (5)
RR Cet		0.45	5979	−1.38 (4)
RR Cet		0.26	6116	−1.29 (6)
DX Del	39367.340+0.472617[1]	0.21	6799	−0.31 (5)
DX Del		0.48	6141	−0.38 (8)
DX Del		0.59	6041	−0.41 (6)
CS Eri	38417.087+0.311331[1]	0.12	6928	−1.36 (4)
CS Eri		0.31	6679	−1.45 (4)
XZ Gru	38260.438+0.34741[1]	0.68	6158	−1.37 (6)
XZ Gru		0.03	6068	−1.12 (5)
XZ Gru		0.43	6029	−1.36 (7)
IK Hya	38461.510+0.65[1]	0.25	6373	−1.24 (1)
FW Lup	42171.377+0.4841712[1]	0.80	6506	−0.11 (7)
FW Lup		0.14	6405	−0.26 (9)
FW Lup		0.36	6294	−0.14 (7)
FW Lup		0.47	6164	−0.27 (10)
VY Nor	25535.249+0.375305[1]	0.63	6000	−2.01 (1)
VW Scl	27809.381+0.510915[1]	0.15	7121	−0.84 (4)
VY Ser	38466.244+0.714096	0.82	6024	−1.30 (6)
VY Ser		0.21	6335	−1.53 (3)
VY Ser		0.54	5969	−1.65 (2)
MT Tel	42206.35+0.316897[1]	0.57	6832	−1.64 (2)
MT Tel		0.92	7085	−1.62 (2)
AM Vir	26859.275 +0.615089[1]	0.12	6493	−0.74 (6)
AM Vir		0.20	6037	−1.11 (5)
AM Vir		0.53	5932	−1.30 (1)
UU Vir	46878.822+0.475606[2]	0.31	6359	−0.70 (7)

1: Kholopov et al. (1990); **2:** Jones et al. (1988); **3:** Fernley & Barnes (1996).

generally have lower S/N, the error in EW is higher and we estimate 10%.

Synthetic equivalent widths were calculated for a grid of temperatures and metallicities using the spectrum synthesis code XLINOP and the ATLAS8 models (Kurucz 1979). Log gf values were taken from Thévenin (1989) (Table 6). The abundance values were calculated by computing the sum of squares of the differences between the observed equivalent widths and the synthetic equivalent widths for five values of metallicity. The sum of squares were then plotted against the metallicities and a parabola was fitted, the adopted metallicity being the minimum of the parabola. In order to check the internal consistency of the whole process we have calculated the abundances of Procyon (HR 2943) and some other standard stars. A microturbulence of 2.0 km s^{-1} and a surface gravity of $\log g = 4.0$ were used for all the stars. The results are given in Table 3. Comparing these values and those obtained from the literature shows good agreement (mean difference and a standard deviation of 0.03 ± 0.09 dex).

The microturbulence velocity has been set to $\xi = 3.6$ km s^{-1} (Lambert et al. 1996) for most of the RR Lyrae stars since the scattered in the abundances derived from the lines was too large or the number of lines used too small to distinguish any systematic differences in the abundances derived from weak and strong lines. Also, following Fernley & Barnes (1996), a value of $\log g = 2.75$ was adopted for all the RR Lyrae stars.

The derived abundances from the individual RR Lyrae spectra are listed in Tables 4, 5. For stars with two or more abundance determinations it can be seen that there is good agreement, the differences are typically ±0.1 dex.

The final abundance for each RR Lyrae star is listed in the Appendix. Also listed are values from the literature. The two sets of values are compared in Fig. 1 where it can be seen that, with the exception of XZ Aps, there is reasonable agreement (rms of the difference 0.18 dex). Since the literature values have a typical error of ±0.13 dex, this rms difference implies a similar error in our work although there is some suggestion that our metallicities are systematically higher (mean difference 0.07 dex). The sensitivity of the derived abundances on the atmospheric parameters has also been studied. Errors of $\Delta T_{\rm eff} = 150$ K and $\Delta\xi = 0.3$ km s^{-1} have been assumed for effective temperatures and microturbulence velocities which produce errors of Δ[Fe/H] = 0.16 dex and Δ[Fe/H] = 0.12 dex respectively. The influence of the errors in $\log g$ on the derived abundances is negligible.

From Tables 4, 5 we can see that stars with abundances calculated at phases out of the minimum light interval show good agreement with the values calculated at minimum light even if at these phases the stellar atmosphere may suffer from fast acceleration which produces large ranges in the physical parameters in a very short time-scale. Clementini et al. (1995) also found similar results. The explanation of this is related to the fact that the steepest variations in a $T_{\rm eff}$-phase diagram only occurs in the interval $0.9 \leq \phi \leq 0.0$ (Fernley et al. 1989). In the rest of the phase interval the variation of $T_{\rm eff}$ is such that, if the ephemeris are accurate enough, the temperature can be determined with a small error. This is also valid for the variations in gravity (e.g. Liu & Janes 1990) with the additional advantage of the little influence of $\log g$ on the abundance determination.

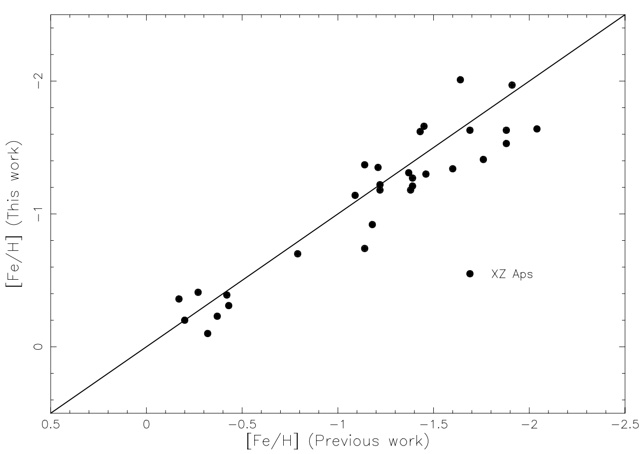

Fig. 1. A comparison between the [Fe/H] values of the present work and previous work

Table 6. Adopted atomic parameters. Log gf values and lower level energies were taken from Thévenin (1989) and Kurucz & Peytremann (1975) respectively

Identification	Log gf	Lower level energy (cm^{-1})
Fe I λ 415.1945	−1.570	28604.605
Fe I λ 415.2056	−0.990	32873.617
Fe I λ 415.2169	−3.180	7728.056
Fe I λ 415.3899	−0.590	27394.688
Fe I λ 415.4098	−1.500	27394.688
Fe I λ 415.4500	−1.040	22838.318
Fe I λ 415.4805	−0.640	27166.818
Fe I λ 417.6577	−0.680	27166.818
Fe I λ 418.7047	−0.660	19757.033
Fe I λ 418.7588	−1.320	27666.346
Fe I λ 418.7617	−2.410	29356.740
Fe I λ 418.7795	−0.650	19562.439
Fe I λ 419.5329	−0.720	26874.548
Fe I λ 419.5618	−1.710	24335.760
Fe I λ 419.6208	−0.920	27394.688
Fe I λ 419.6533	−2.190	23783.613
Fe I λ 421.3653	−1.550	22946.809
Fe I λ 421.9355	−0.720	28819.945
Fe I λ 421.9419	−1.650	24118.814
Fe I λ 422.2221	−0.980	19757.033
Fe I λ 425.0130	−0.350	19912.494
Fe I λ 425.0787	−1.040	12560.930
Fe I λ 425.0893	−2.040	24772.018
Fe I λ 440.4080	−2.530	31686.346 *
Fe I λ 440.4750	−0.250	12560.930 *

* Only used in metal-poor RR Lyraes (saturation effects may occur in metal-rich RR Lyraes).

5. Missclassified and unusual stars

The following stars were included in the HIPPARCOS list of RR Lyraes but are probably not RR Lyraes:

1. **CW Lup**. Our spectra show a constant velocity of 31.7 km s^{-1} based on 3 well-placed observations. The HST Guide Star Catalogue shows a star at exactly the HIPPARCOS coordinates and this is the star we observed (α(2000.0) = $14^{\rm h}20^{\rm m}28.2^{\rm s}$; δ(2000.0) = $-44^{\rm d}31^{\rm m}56^{\rm s}$). However, there is another star of similar brightness approximately 1 arcmin away and probably this is the variable.

2. **UY Scl**. Our spectra show a star of much later spectral type (weak Hγ, strong molecular absorption bands) with radial velocity variations of $\approx$ 40 km s^{-1}. A search of the HST Guide Star Catalogue at the HIPPARCOS position (α(2000.0) = $00^{\rm h}14^{\rm m}45.7^{\rm s}$; δ(2000.0) = $-39^{d}14^{m}36^{s}$) shows no other star of

similar brightness within a 6 arcmin radius. The star is clearly a variable but has been missclassified as an RR Lyrae.

3. **IV Pav**. The GCVS lists this star as having $\Delta V = 0.4$ but no period is given. Our spectra show a variable radial velocity, $18 \leq vr \leq 39$ km s^{-1}, but the lines are broader and shallower than for other RR Lyraes. Probably the star is a short-period Eclipsing Variable.

4. **FW Lup** and **IK Hya**. Both these stars showed relatively small velocity amplitudes. The GCVS also shows they have relatively small light amplitudes (FW Lup $\Delta V = 0.40$ and IK Hya $\Delta V = 0.46$). The stars therefore show the characteristics of the so-called Anomalous Cepheids, namely the periods imply fundamental mode pulsation (FW Lup P = 0.48 days, IK Hya P = 0.65 days) but the light and velocity curves are more compatible with overtone pulsation. For further discussion of Anomalous Cepheids see Teays & Simon (1985) and for other candidate stars see Paper I.

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