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More light on RV Tauri variables*

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Abstract. This study confirms the results of the preliminary study (Russell, 1997) indicating that RV Tau variables in globular clusters don't show the kind of anomalous abundances seen in RV Tau variables observed in the field. By making comparisons with red giants in the same clusters, it has been possible, for the first time, to identify precisely how each element deviates from the normal abundance ratios of evolved giants.

The apparent systematic deficiency in s-process elements reported for RV Tau variables in the literature is not confirmed in the present study. Either the stars observed here are of such low metallicity, that what ever process causes s-process deficiencies in more metal rich field stars doesn't operate; or the systematic deficiency in s-process elements is simply an illusion of small number statistics.

Key words: stars: abundances – stars: asymptotic, post-asymptotic giant branch (AGB, post-AGB) – stars: variables: other – globular clusters: general

1. Introduction

RV Tau variables are one of several classes of low mass variable stars thought to populate the region of the HR Diagram to the left of the AGB-branch, and above the horizontal branch. These stars appear to be at the very end of their evolution along the asymptotic giant branch (AGB), or post-AGB stars. The standard picture of this stage of evolution is of an electron degenerate C-O core, with overlying layers of He and H. Mixing between the two outer layers should result in enhancement of the surface layers with s-process elements, the by-products of neutron capture reactions occurring during He-burning. So investigation into the s-process abundances should reveal valuable insights into the nature of the stars.

Although there has been very little work done on the detailed elemental abundance analyses of RV Tau variables, and stars like them, what has been done (Aliev, 1967; Baird, 1979; Yoshioka, 1979; Luck and Bond, 1984 & 1989; Giridhar et al., 1994), reveals evidence for systematic s-process *under-abundances*. This has serious implications for our accepted view of AGB evolution, and the nature of RV Tau variables.

Luck and Bond (1989) noted that the s-process abundances were reminiscent of those found in extreme halo red giants. Yet RV Tau variables have much higher metallicities than extreme halo stars. Luck and Bond suggest that either:

1. the stars reflect their original s-process deficiencies relative to Fe, but severe mass-loss has reduced the hydrogen abundance in the atmosphere, thereby raising the Fe/H ratios to the observed levels.
2. the stars have normal s-process abundances, but because of their low 2nd ionization potentials, these elements are selectively over-ionized by Lyman-continuum photons. The key to this possibility is the observed systematic deficiency in Sc in these stars; the only light metal that shares a sufficiently low 2nd ionization potential.

These two alternatives could be tested by observing RV Tau variables in globular clusters, and comparing them with their red giant companions. If a hydrogen deficiency is the cause of the s-process deficiencies, RV Tau variables should show higher [Fe/H] ratios than the normal red giants, but the same [s- process/Fe] ratios. If over-ionization is the cause, RV Tau variables should show the same [Fe/H] ratios as the red giants, but lower [s-process/Fe] ratios.

Giridhar et al. (1994) pointed out that there were so few detailed abundance studies of RV Tau variables in the literature, that any patterns in their abundances are impossible to discern. Since there are just six stars studied in the literature, this survey of 3 stars adds considerably to the total number of RV Tau variables analysed. It is not unreasonable, therefore to reanalyse the complete data set in this work, to look for patterns that may be present.

2. Observations

The globular cluster programme stars are listed in Table 1, together with the photometric parameters derived from the literature. The variables were chosen from the work of Sawyer (1955), and Sawyer Hogg (1973) (see column 7). Although the variable M56_V6 is almost certainly of RV Tau class, M2_V6

* Tables 5, 6, 7, 9, and 10 are 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

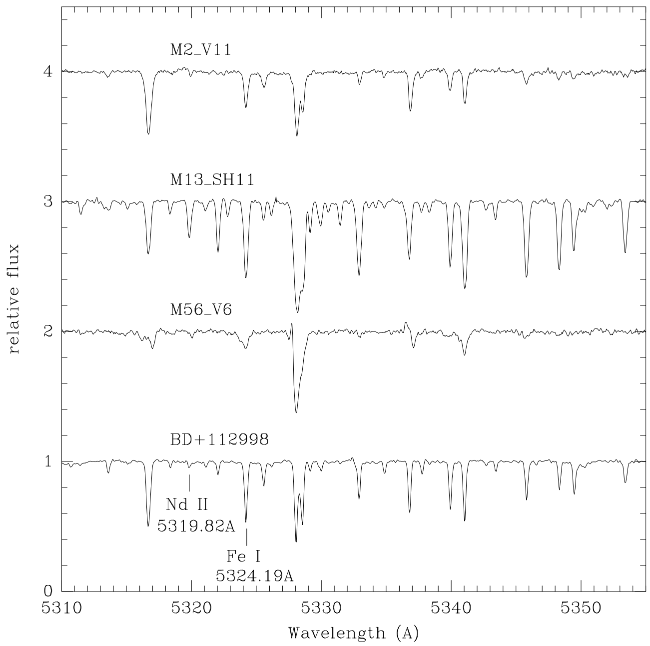

Fig. 1. Example spectra

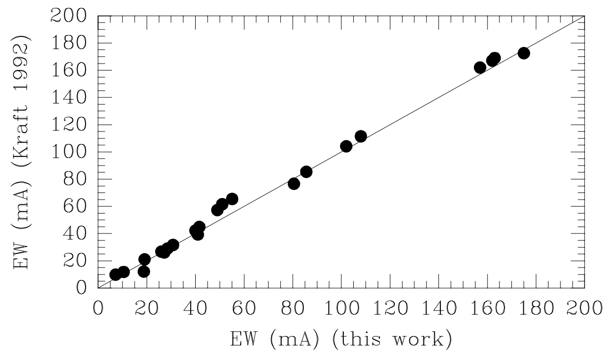

Fig. 2. Comparison of equivalent widths between this work and Kraft et al. (1992)

and M13_SH11 need further confirmation (see Demers (1969); Eggen (1986)). Companion red giants were selected from various references shown in column 7, and were chosen to be bright, not excessively red or crowded, and having, if possible, previous spectroscopy or accurate photometry reported in the literature.

Observations were made in July 1993, with the Utrecht Echelle Spectrograph (UES) on the 4.3m William Herschel Telescope (WHT), at the Observatorio Roque de los Muchachos, La Palma. The resolution was around 50,000 with the Tek CCD, the wavelength coverage mostly complete from 4650 – 7160A (falling off towards the red end), and the signal to noise ratio (S/N) in the range 70 to 180. Several exposures of 1800 seconds were made of each star, to ensure good cosmic ray removal, and adequate S/N.

3. Reduction and analysis

The spectra were reduced using standard IRAF software running on a SUN SPARC station at the Dublin Institute for Advanced Studies. The overscan values and the averaged bias exposures were subtracted, the data trimmed to remove the overscan and edge columns of the CCD, and the data divided by averaged and normalized flat fields. One dimensional spectra were extracted, and were wavelength calibrated using ThAr arc lamp spectra. The different spectra of each star were weighted and combined to form single spectra. The continua were set automatically using a low order polynomial fit to the uncontaminated continua. On occasions when this procedure was clearly unsatisfactory, the continua were set manually. The line strengths were measured by fitting Gaussians to the line profiles. Example spectra are illustrated in Fig. 1, where a Nd II and a FeI line are marked.

Line transition probabilities were taken from the literature, using the highest quality, and most up to date measures available. These are reported, together with the measured equivalent widths in Tables 9 and 10 in the appendix (available in electronic format from CDS – Centre de Données astronomiques de Strasbourg). The abundances were determined using the fine abundance analysis program WIDTH6 (Bessell & Norris 1984). This programme uses iterative spectrum synthesis, whereby abundances are adjusted until equivalent widths of model lines match those of the measured lines. The results were so good in nearly all cases, that little additional adjustment of the *gf*-values was required.

In the majority of cases, only line strengths of less than 100mA were used in the analysis. The notable exceptions were the lines of BaII, which in most cases, were still less than 200mA. No corrections were made for hyperfine splitting, as these were not important in determining the abundances of the n-capture elements, of interest in this work.

The only comparison that could be made with equivalent widths quoted in the literature, was with the work of Kraft et al. (1992). These authors measured lines in 4 stars in common with this work, including M13_I_13. The comparison is shown graphically in Fig. 2, where the line represents strict equivalence. The agreement in excellent, with the average difference (this work minus Kraft et al. (1992)) of -2.2$\pm$4.2mA. It is clear that abundance errors due to measurement errors are negligible except for the very weakest lines.

The atmospheric parameters are shown in Table 2. Although adequate photometry was available in some cases, for consistency, all stars were analysed using only spectroscopic criteria to determine the atmospheric parameters. The consistency of the results with those from the literature was checked to determine the efficacy of the procedures.

The effective temperatures were determined by requiring that the iron abundances determined from FeI, were independent of excitation potential. This was accurate to within the model atmosphere grid spacing of $\pm$125K (Kurucz 1992). The gravities were determined by requiring the abundances of iron derived from FeI and FeII lines, should match (log g $\pm$0.5 cm s^{-2}). The microturbulent velocities ξ_T, were determined by re-

Table 1. Photometric parameters of programme stars

Star	Class	V	$B-V$	[Fe/H]	P (days)	Ref[a]
M2_V11	RV Tau	12.5-14.0	0.56	...	67.1	S55
M2_HII_89	Red Giant	13.22	1.45	-1.7	...	S88,H75
M13_SH11	RV Tau	12.9-13.8	...	...	92.5	SH73
M13_I_13	Red Giant	12.54	1.28	...	...	CM79
M56_V6	RV Tau	12.9-14.8	...	...	90.0	S55
M56_I_60	Red Giant	13.54	1.42	...	...	B65
M56_I_96	Red Giant	13.29	1.46	...	...	B65

[a] S55 = Sawyer (1955); S88 = Suntzeff et al. (1988); H75 = Harris (1975); SH73 = Sawyer Hogg (1973); Cudworth and Monet (1979); B65 = Barbon (1965)

quiring the iron abundances derived from FeI be independent of equivalent width (ξ_T $\pm$0.5 kms^{-1}). This required the use of stronger Fe I lines, to ensure that an accurate value of the parameter was measured for use, especially, with elements having *only* strong lines. Metallicities of the model atmospheres were kept at a constant value of [Fe/H] = -1.5, since this was taken to be unknown a priori. The resulting errors (see Table 4) were not significant enough to require reanalysis at more exact metallicities. The abundances were calculated using the WIDTH6 modeling code, with recent hydrostatic, plane-parallel model atmospheres, assuming LTE (Kurucz, 1992). Table 3 details the physical parameters derived for the standard stars, and compares them with the most recent values quoted in the literature. The agreement is very close, and gives grounds for believing the methods used here are sound.

4. Results

The results are detailed in Tables 5, 6 and 7 (available in electronic format from CDS), where the solar abundances, except for Fe, come from Anders and Grevesse (1989). The Fe abundance is derived from Johansson et al. (1994). These are shown graphically in Figs. 3, 4 and 5, which show the relative abundances of the RV Tau variables and their red-giant companions, where:

$$[M/Fe]^* = log(N/\mathrm{Fe})_{\mathrm{RVTau}} - log(N/\mathrm{Fe})_{\mathrm{redgiant}}$$

The filled circles denote elements for which there are at least two spectral lines measured from each star. The open circles, without error bars, are for those elements with only one spectral line in one or both of the stars. For comparison purposes, differential abundances are also displayed with the metal poor star BD+11°2998.

The errors in the figures illustrate only the line to line variations. Errors due to uncertainties in the physical parameters are of the order of $\pm 0.2dex$ for most elements, although higher error of up to $\pm 0.5dex$, are observed in some of the lighter elements. An illustration of possible modelling errors is presented in table 4, for the particular case of M13_SH11. Notice how much more robust the metal-to-iron ratios are, compared with the metal-to-hydrogen ratios.

Table 2. Derived physical parameters of the stars in this study

Star	Class	T$_{eff}$	log g	ξ_T	[Fe/H]
BD+11°2998	field star	5400	2.0	2.0	-1.16
HD 204543	field star	4700	1.4	2.0	-1.70
HD 165195	field star	4500	1.0	2.5	-2.14
BD+30°2611	field star	4300	1.0	1.7	-1.28
HD 135148	field star	4250	0.5	2.0	-1.81
M2_V11	RV Tau	5750	0.5	3.0	-1.78
M2_HII_89	Red Giant	4000	0.0	1.7	-1.55
M2_HII_89[a]					*-1.7*
M56_V6	RV Tau	4500	1.0	2.0	-3.33
M56_I_60	Red Giant	4450	1.0	2.0	-1.80
M56_I_96	Red Giant	4500	1.0	2.0	-1.68
M13_SH11	RV Tau	4250	1.0	2.0	-1.37
M13_I_13	Red Giant	4250	1.0	1.7	-1.37
M13_I_13[b]		*4290*	*1.0*	*2.0*	*-1.45*

[a] Suntzeff et al. (1988)
[b] Kraft et al. (1992)

4.1. M2

The RV Tau variable M2_V11 is particularly enhanced in abundances of the odd-elements Na and Al, relative to the red giant M2_HII_89, as well as in the the α-element Si. The elements Na and Al are diagnostics of H-burning at the high temperatures of the ON-cycle. These, together with the slight over abundances of some of the s-process elements - Y and Ba, may be an indication that normal third dredge-up has occurred in the RV Tau variable.

Since the Fe abundance is within 0.2dex of the red giant's, and Sc is of perfectly normal abundance, it seems that neither contention of Luck and Bond (1989) are supported. Comparison with the control star BD+11°2998 confirms all the results derived from the red giant differential analysis.

One possible alternative view is that RV Tau variables are post-AGB stars showing evidence for deposition on to grains, as was found for IW Car by Giridhar et al. (1994). Key abundance

Table 3. Physical parameters of the standard stars

Star	V	$(B-V)$	$(V-R)$	T_{eff}	log g	ξ_T	[Fe/H]	Ref[a]
BD+11°2998	9.07	0.67	0.606	5350	2.0	2.0	-1.38	K92
				5420	3.00	...	-0.9	G84
				5400	2.0	2.0	-1.16	This work
HD 204543	8.29	0.92	0.817	4750	1.50	2.00	-1.64	K92
				4710	1.23	1.5	-1.88	G89
				4620	1.20	2.0	-1.77	G88
				4700	1.4	2.0	-1.70	This work
HD 165195	7.32	1.29	1.06	4500	1.30	2.4	-2.25	S91
				4507	1.45	2.2	-2.22	GS91,94
				4500	1.5	2.8	-2.25	SC88
				4500	1.5	2.8	-2.23	G88
				4500	1.0	2.5	-2.14	This work
BD+30°2611	9.17	1.18	0.960	4290	1.00	1.75	-1.19	K92
				4420	0.9	1.7	-1.2	LB85
				4300	1.0	1.7	-1.28	This work
HD 135148	9.49	1.21[b]	...	4270	0.5	2.0	-1.8	LB85
				4250	0.5	2.0	-1.81	This work

[a] K92 = Kraft et al. (1992); G84 = Gratton et al. (1984); G89 = Gratton (1989); G88 = Gilroy et al. (1988); S91 = Sneden et al. (1991); GS91 = Gratton and Sneden (1991); GS94 = Gratton and Sneden (1994); SC88 = Sneden and Crocker (1988); LB85 = Luck and Bond (1985)
[b] Transformation from b-y according to Crawford (1975)

Table 4. Modelling errors from uncertainties in physical paremters

Element	ΔT = +250K	Δlogg = +0.5	$\Delta\xi$ = +0.5kms^{-1}	$\Delta[M/$H] = -0.5dex
Ti I	+0.49	-0.05	-0.19	+0.12
Ti II	-0.08	+0.19	-0.22	-0.06
Cr I	+0.32	-0.05	-0.11	+0.11
Cr II	-0.21	+0.17	-0.07	-0.05
Fe I	+0.13	+0.01	-0.13	+0.07
Fe II	-0.29	+0.22	-0.07	-0.06
[TiI/FeI]	+0.36	-0.06	-0.06	+0.05
[TiII/FeII]	+0.21	-0.03	-0.15	0.00
[CrI/FeI]	+0.19	-0.06	+0.02	+0.04
[CrII/FeII]	+0.08	-0.05	0.00	+0.01

changes expected in this case would be a reduction in [Fe/H] by 1.0dex, a reduction in [Sc/H] and [Ca/H] by 2.0dex, and a slight enhancement in [Zn/H] by 0.2dex. None of these were found.

4.2. M13

The RV Tau variable M13_SH_11 shows much less scatter about the normal Fe abundance, relative to the red giant M13_I_13, than for M2_V11. There are four elements with obvious overabundances in M13_SH_11, the odd elements Na and Al (as for M2_V11), and Ba. The fact that Ba is again significantly high is interesting. Unfortunately, the abundances of Ba are derived from strong to very strong lines, and as such, are not dependable. At the very least, there is no evidence for any s-process element underabundance. Nor is there any underabundance observed for Sc. Since the Fe abundance is within 0.05dex of the M13_I_13 Fe abundance, again there is no support for either contention of Luck and Bond (1989), nor is there any s-process underabundance. In addition, there is no sign of deposition onto dust grains.

When comparisons are made with the control star BD+11°2998, we see that, although ZrI becomes severely underabundant, the neutron capture elements beyond Ba, are systematically enhanced. The enhancement in the heaviest elemental abundances was also observed in M2.

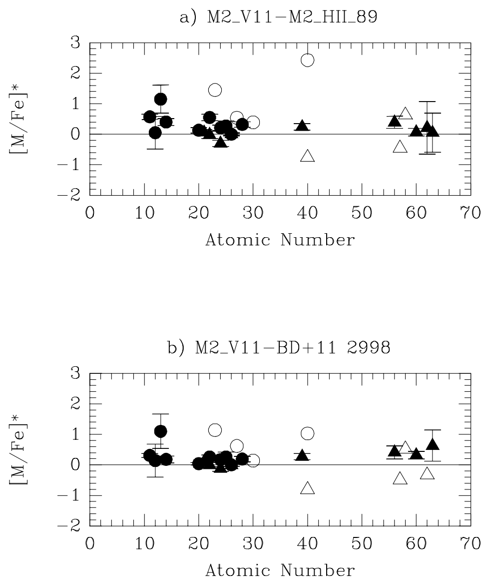

Fig. 3a and b. Relative metal to iron abundances between the RV Tau star M2_V11 and **a** the red giant M2_HII_89, **b** the metal poor star BD+11°2998

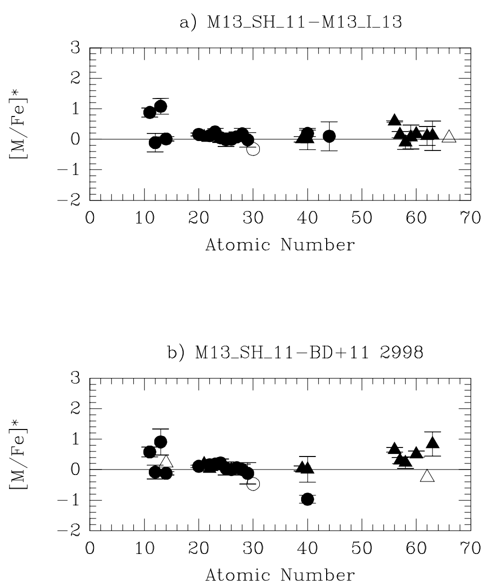

Fig. 4a and b. Relative metal to iron abundances between the RV Tau star M13_SH_11 and **a** the red giant M13_I_13, **b** the metal poor star BD+11°2998

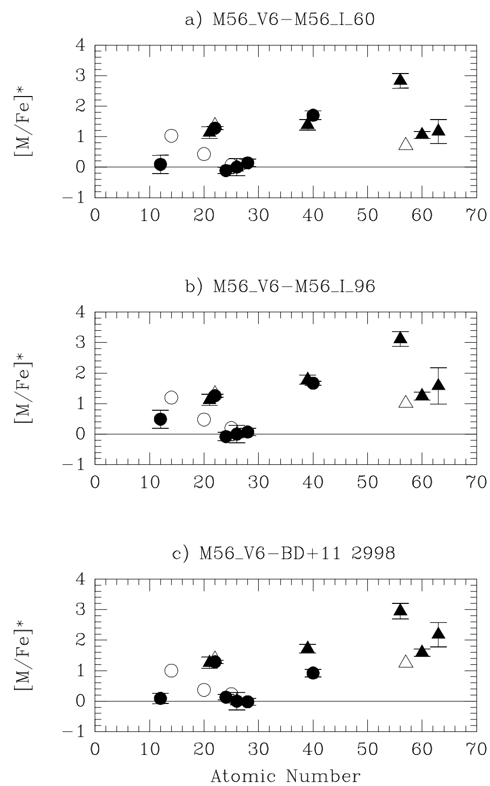

Fig. 5a–c. Relative metal to iron abundances between the RV Tau star M56_V6 and **a** the red giant M56_I_60, **b** the red giant M56_I_96, **c** the metal poor star BD+11°2998

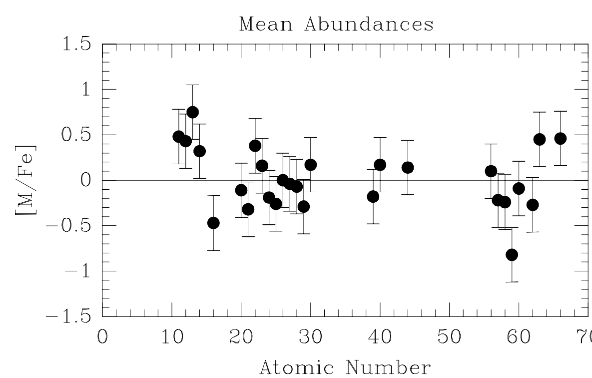

Fig. 6. Mean metal to Fe ratios, relative to solar, for RV Tau variables as a class

4.3. M56

The most puzzling star of the sample studied, was the RV Tau variable star M56_V6. Most lines of Fe were in agreement with a massive 1.7dex underabundance relative to the two red giants studied from M56. Excellent agreement was observed with this value and the Cr, Mn, and Ni abundances. However, four lines of Fe, and several other element abundances, including Sc, Ti and all the s-process elements, are vastly enhanced in abundance relative to the derived Fe abundance, and close to the abundances in the red giant companions (within ∼0.3dex).

The five Fe lines in question are those at 4930A; 5060A; 5247A; 5250A; and 5373A. The line at 4930A is particularly strong, indicating an abundance of 6.12, but the other four lines are closely grouped, with an average abundance of 5.41 ± 0.05dex. The five Fe lines show no systematic property that may distinguish them from the majority of the lines. Two lines, including the one at 4930A, have a high excitation potential,

Table 8. [M/Fe] for RV Tau variables as a class

Element	A	M2_V11	M13_SH11	M56_V6	IW Car	LB_mean[1]	Mean
Na	11	0.31	0.58	...	0.34	0.55	0.48
Mg	12	0.50	0.28	1.70	-0.98	0.49	0.43
Al	13	1.06	0.87	...	...	0.53	0.75
Si	14	0.49	0.22	1.31	-0.57	0.28	0.32
S	16	...	...	...	0.36	...	0.36
Ca	20	0.23	0.30	0.56	-1.97	0.00	-0.11
Sc	21	0.11	0.19	1.26	-2.13	-0.49	-0.32
Ti	22	0.27	0.24	1.48	...	0.09	0.38
V	23	1.10	0.14	...	...	0.01	0.16
Cr	24	-0.12	0.03	-0.05	-0.98	-0.10	-0.19
Mn	25	-0.16	-0.38	-0.19	...	-0.28	-0.26
Fe	26	0.00	0.00	0.00	0.00	0.00	0.00
Co	27	0.79	-1.10	...	...	0.07	-0.04
Ni	28	0.16	-0.03	-0.05	-0.96	0.08	-0.07
Cu	29	...	-0.29	...	...	-0.29	-0.29
Zn	30	0.37	-0.24	...	-0.04	0.30	0.17
Y	39	-0.05	-0.28	1.40	...	-0.72	-0.18
Zr	40	0.91	0.32	2.29	...	-0.83	0.17
Ru	44	...	0.14	...	...	...	0.14
Ba	56	0.49	0.73	3.03	-1.91	-0.38	0.10
La	57	-0.74	0.05	1.00	...	-0.55	-0.22
Ce	58	0.10	-0.19	...	...	-0.53	-0.24
Pr	59	...	0.13	...	...	-1.77	-0.82
Nd	60	0.00	0.19	1.27	...	-0.66	-0.09
Sm	62	0.33	0.41	...	-0.54	-0.61	-0.27
Eu	63	0.37	0.58	1.92	...	-0.05	0.45
Dy	66	...	0.46	...	...	...	0.46

while the other three have very low excitation potentials. The equivalent widths span the full range from 8mA to 96mA.

Is it possible that we are witnessing here the effects of grain deposition? The elements Fe, Cr and Ni are depleted equally, and are consistent with grain deposition. The critical element in this case, however, is Ti. According to Federman et al. (1993), Ti should be as depleted as Fe, or more so. The evidence remains, that Ti is much less depleted than Fe in M56_V6.

5. RV Tau variables as a class

It is important to consider whether we can say anything new about the systematic characteristics of the elemental abundances of RV Tau variables as a class. In Table 8 the solar differential abundances are listed for all the stars studied here, and in the literature. In deriving the mean for RV Tau variables as a class, equal weight was given to the mean of the five stars in Luck & Bond (1989), and to IW Car plus the three stars from this work. The results are shown graphically in Fig. 6. Here the error bars of $\pm$ 0.3dex, are for illustrative purposes only. The set of stars is so disparate and small, that it is meaningless to attempt calculating more representative errors. Nevertheless, 0.3dex should be considered conservative.

From Fig. 6 we see that there is no evidence for a systematic underabundance in the s-process elements. The only element falling significantly below zero is Pr, and as this is poorly determined, it is not considered significant. Interestingly, Eu and Dy are the only two n-capture elements that appear slightly over-abundant. While Dy is poorly determined, Eu is somewhat more reliable. Both elements are mainly r-process in origin, rather than s-process. However, Sm is thought to be 70% r-process in origin (Gratton & Sneden, 1994), and does not share the over-abundance of the two heavier elements.

At the other end of the scale, both odd elements Na and Al are significantly over-abundant, indicating 3rd dredge-up contamination. The α-elements Mg, Si, S and Ti[2] are all enhanced, while Ca is not at all. Again, this could be evidence for dredge-up of processed material.

6. Conclusions

What ever process might be responsible for producing s-process under-abundances for stars in the field with $[Fe/H] > -1.6$, is not observed to be in operation for the stars observed here. If mass loss were in operation, the [Fe/H] abundance ratios would appear higher in the RV Tau variables, than in the red giants. In fact, they are all lower in abundance, to a greater or lesser extent. If over-ionization were operating, the s-process element

[2] not strictly an α element

abundances would be lower in the RV Tau variables than in the red giants. If anything, these elements are higher in abundance. Certainly the element Sc shows no sign of depletion.

There is also no evidence that we are seeing the effects of grain deposition in any of the stars studied here. Taking RV Tau variables as a class, including all analyses from the literature, there is no evidence for a systematic s-process element under-abundance, nor for grain deposition. There is conceivably some significance in the systematic overabundances of the r-process elements Dy and Eu, and in the odd-elements Na and Al. However, a much larger sample needs to be studied before conclusions can be drawn on the systematics of the abundance ratios of the class of RV Tau variables as a whole.

Perhaps the most significant conclusion to be drawn from the present work, is that RV Tau variables are *not* a homogeneous class of stars at all. It seems more likely that they include stars from several different stages of evolution. The alternative, that some other parameter, like stellar mass or metallicity, has a large effect on the elemental abundances, will not explain such peculiar stars as IW Car and M56_V6.

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Appendix A

The equivalent widths (in mA) for all the lines measured in this programme are detailed in Tables 9 and 10. In Table 10 the log gf values used in the analysis are given in column 4, with the associated references in column 5. The only log gf values that needed adjusting were ZrII 4772.31 and 5112.28. These were changed by -2.25 and -1.39, respectively, to bring the abundances due to these lines up to the average abundances from the other ZrII lines for the stars in M13.

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