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Abundance Analysis of the Long Period Southern Cepheid RZ Vel

Sunetra Giridhar *Indian Institute of Astrophysics, Bangalore 560034*

A. Arellano Ferro *Institute de Astronomia, Universidad Nacional Autonoma de Mexico, Ap. Postal 70-264, Mexico D. F., 04510*

Aruna Goswami *Indian Institute of Astrophysics, Bangalore 560034*

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Abstract. The long period classical cepheid RZ Vel (HD 73502) is known to be a member of an OB association, Vel OB1 in Vela, and a high metallicity is ascribed to it by the photometric work of Eggen (1982). We have done an abundance analysis for this long period (P = 20.4 days) and hence young (age ≈ 1.80×10^7 yr) classical cepheid using high resolution CCD spectra with good S/N ratio. We have used a detailed model atmosphere method to derive the abundances of the light elements C, O, A1, S and of many Fe-peak elements and a few s-process elements. Our present work indicates near solar abundance for most of the elements for RZ Vel and hence we do not confirm the high metallicity derived photometrically by Eggen (1982) for this star.

Key words: classical cepheids, abundances—OB association

Introduction

Owing to their relative youth long period classical cepheids are known to be very valuable objects for the study of the metallicity of the Interstellar Medium (ISM). If the long period classical cepheid happened to be a member of a cluster or an association, then it could also be used for calibration of the P–L–C relationship of cepheids, which is one of the important tools for determining distances. Further, the abundances of such classical cepheids due to the good estimates of their distances have also been used in deriving the Galactic abundance gradient (Luck 1982a; Luck 1982b; Giridhar 1983; Harris & Pilachowski 1984 and others).

It is well known that calibration of the P–L–C relation requires a precise knowledge of interstellar reddening and this factor is normally taken into account with the aid of multicolour photometry. It was shown by Caldwell & Coulson (1985) that metallicity affects the intrinsic line in the (B — V) *vs* (V— I) diagram which in turn would affect the reddening estimate. As a result the coefficient of the P–L–C relation will also be affected.

Eggen (1982) has studied RZ Vel and two other cepheids in the Vela region using a photometric system that is a modified version of the Strömgren system and has derived a very high metallicity for this star. From Fig. 14 of Eggen (1982) using [Fe/H] = – 4.0 Δ[M1] – 0.06 and Δ [c1] = –Δ[M1] we obtain [Fe/H] ≈ 2.0 dex.

These considerations prompted us to carry out a detailed abundance analysis of RZ Vel employing high resolution CCD data and a detailed model atmosphere method.

We have presented in Table 1 the description of our observations and the derived atmospheric parameters. Section 2 contains a description of our observational data and the reduction procedure. We have described our abundance analysis in Section 3 and the results are discussed in Section 4. Section 5 contains the discussion and conclusions.

2. Observations and data analysis

High resolution CCD spectra were obtained using the coudé echelle spectrograph with the 1 m reflector of the Vainu Bappu Observatory, Kavalur, India. The spectrograph gives a reciprocal linear dispersion of 8 Å mm^{-1} when used with a camera of 10 inch focal length. The format of the CCD is 384 × 576 pixels of size 23 μm^2. One pixel corresponds to 0.18 Å in our configuration. The FWHM of the instrumental profile is derived using the mean value for many unsaturated lines of a hollow cathode Th +A lamp (used for wavelength calibration) and is found to be 0.45 Å. In addition, the FWHM of telluric lines in the 6200 Å region also indicates a value of 0.45 Å for the instrumental profile.

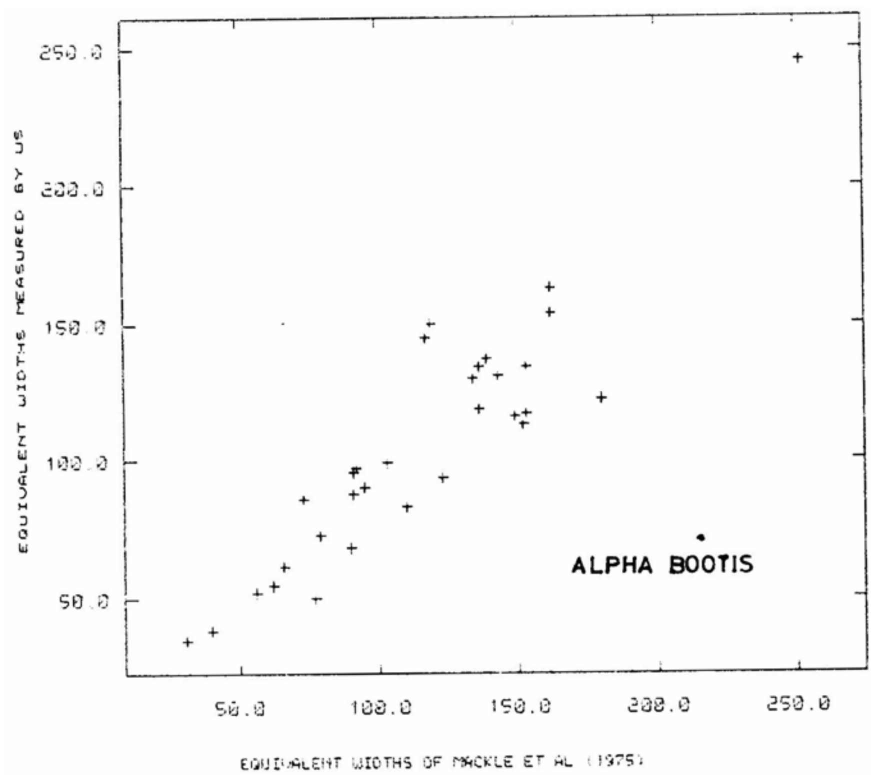

Figure 1. Equivalent widths measured by us are compared with those of Mäckle *et al.* (1975) for alpha Bootis.

The performance of this instrument and the accuracy attained in equivalent width measurements is described in Goswami & Giridhar (1990). These authors have measured the equivalent widths of a large number of lines for two well known stars Procyon and Arcturus. High resolution spectral atlases of these stars have been published by Griffin (1968) and Griffin & Griffin (1979). Our measured equivalent widths have been compared with those of Mäckle *et al.* (1975) in Fig. 1.

Our internal errors are better than 15 per cent for lines with equivalent widths in the range of 50–150 mÅ and better than 10 per cent for the stronger lines. The errors are larger for the weaker lines (equivalent width range 10–30 mÅ) reaching up to 30 per cent for lines weaker than 20 mÅ and therefore we have not used such lines in our analysis. Most of the lines measured by us were in the equivalent width range 40–250 mÅ. Our spectra were reduced using the spectroscopic data reduction package RESPECT (Prabhu, Anupama & Giridhar 1987, in its upgraded version, Prabhu & Anupama 1990). The extraction of the echelle spectrum follows the algorithm of Horne (1986). The background level due to thermal noise and mean scattered light in the spectrograph is estimated using the counts in interorder rows after removing the effects of cosmic ray hits. A xenon lamp was used for flat field corrections. The flat field corrections were made after removing a low order polynomial in each row. The extracted spectrum orders were linearized in wavelength using a third degree polynomial for wavelength as a function of position. The standard error of the fit is 0.05 Å. The pseudocontinuum was determined using the highest points in each spectrum known to be free of the stellar lines. The spectra were reduced to continuum by the spline interpolated values between these points.

The S/N of the spectra are in the range 50–80 and the accuracy of the measured equivalent widths must lie within a range of 10–15 per cent.

3. Abundance analysis

We have calculated theoretical equivalent widths for the spectrum lines of interest with the assumption of local thermodynamic equilibrium (LTE) in a plane parallel atmosphere in hydrostatic equilibrium. The justification of these assumptions and our method of abundance determination have been explained in detail in Giridhar (1983). Model atmospheres were selected from the grid of models published by Kurucz (1979). Line equivalent widths were calculated using the detailed model atmosphere method with the aid of a computer code originally developed by Sneden (1974). Slight modifications were made by the first author to reduce the computer memory requirement and a few additional opacities *e.g.* due to electron scattering and C, A1, and Mg were included (though the effect of these terms on total opacity is not very large in cepheid atmospheres).

We have shown in Fig. 2 along with the light curves the phases at which our observations were taken. The phases were calculated using the light curve parameters given by Schaltenbrand & Tammann (1971). These points lie on the falling side of the light curve and are near the mean magnitude. At these phases there are no rapid movements in the atmosphere of the star and one is therefore justified in using the assumption of hydrostatic equilibrium.

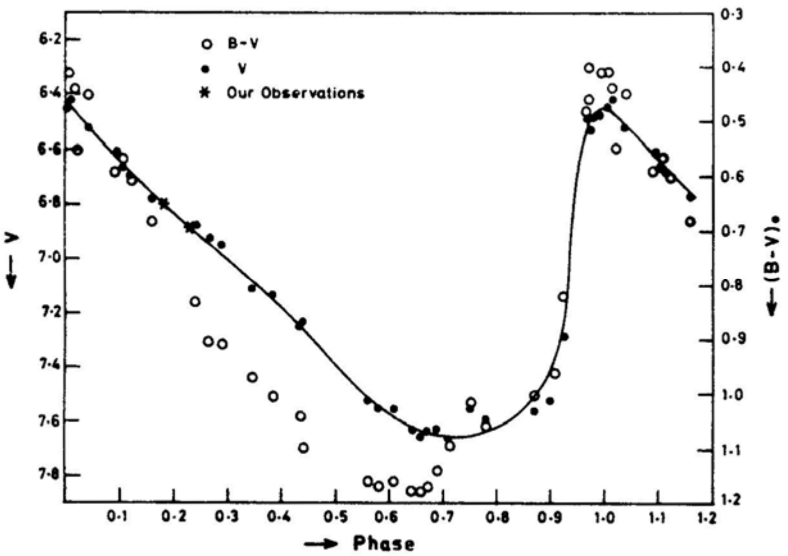

Figure 2. Light curve of RZ Vel using the observation of Mitchell *et al.* (1964). The phases at which our spectra were obtained are shown by * symbol.

3.1 *Determination of Atmospheric Parameters*

Our spectra cover a wavelength range of 4400–6700 Å and many important elements are well represented in this spectral region. We could measure a large number of Fe I and Fe II lines (40 and 15 respectively) and these lines covered a range of 0–5 eV in excitation potential and a range of 40–250 mÅ in equivalent widths. We have limited ourselves to lines with equivalent widths larger than 30 mÅ. At first the micro-turbulence velocity was estimated by requiring the derived abundances to be independent of the strength of the lines *i.e.* lines falling on the linear and flat portions of the curve-of-growth yielding the same abundance value. The effective temperature was obtained by adjusting the temperature such that the derived abundances are independent of the excitation potential of the lines. We have used the ionization balance between Fe I and Fe II lines to derive the gravity.

The atmospheric parameters estimated by us are presented in Table 1. The effective temperatures (6250 K and 6000 K) derived by us at the two phases are systematically larger than the colour temperatures (5800 K, 5600 K) derived using Schmidt-Kaler's (1982) calibration of $(B - V)_0$ for the corresponding phases but a difference of 400 K

Table 1. Observational details and atmospheric parameters.

Date	JD	Phase	T_{eff} °K	log g	V_t Km s^{-1}
10-1-1990	2447901.81	0.18	6250	1.5	5.5
11-1-1990	2447902.78	0.23	6000	1.0	5.5

is not unreasonably large when the accuracies of the estimates are no better than ± 200K.

3.2 *Elemental Abundances*

We began our analysis by measuring abundances of the elements Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Ni using equivalent widths of the unblended lines for these elements. The lines that did not have any known significant line within ± 0.45 Å from the line centre were considered unblended. Originally, more than 70 Fe I lines were measured but 30 out of them were discarded due to the existence of other lines in the close vicinity of these lines. At first the atmospheric parameters were derived using Fe I and Fe II lines. We have selected model atmospheres from the grid of Kurucz (1979). Sometimes we also used interpolated models since Kurucz's models are separated by 500 K in effective temperatures and 0.5 in log g. We have done parabolic interpolation for each layer between the models (for example between models with effective temperatures 5500 K, 6000 K, 6500 K and 7000 K with the same log g or in other cases for a given effective temperature the interpolation was done between models with log g 0.5, 1.0, 1.5, 2.0 *etc*). Our interpolated models are separated by 200 K in effective temperature and 0.20 in log g though interpolation can be done at finer intervals of effective temperature or log g.

The oscillator strengths for Fe I lines were taken from Giridhar & Arellano Ferro (1989) whenever available. The oscillator strengths of many Fe II, Cr I, Cr II, Ti I, Ti II lines were taken from the unpublished compilation of Giridhar & Arellano Ferro. However, for many lines we were forced to use gf values derived from inverted solar analysis. We have used the solar atmosphere model of Holweger & Müller (1974) with depth independent microturbulence velocity of 1.0 km s^{-1}. The solar equivalent widths were taken from Moore, Minnaert & Houtgast (1966). The gf values used in the present work are in excellent agreement with those published by Martin, Fuhr & Wiese (1988).

3.3 *Abundance Measurement of C, O, and s-Process Elements*

These elements present themselves in very few and often blended features. Carbon has three C I lines around the 4766–4775 Å region but only one at 4770.00 Å appears unblended at our resolution, the other two C I lines at 4771.72 Å and 4775.87 Å are blended with Fe I lines. Similar situation prevails for the O I lines. Only one line at 6156.76 Å is unblended, the other two at 6156.03 Å and 6158.17 Å are blended with Fe II lines in the wings. Lines of Ba II at 4554 Å and 6141 Å, those of Ce II in 4560 Å region are also similarly blended.

We have synthesized portions of the stellar spectrum using a suitable model atmosphere for the star and the atomic data of all lines falling in the spectral region. Since the abundances of Fe-peak elements were determined earlier using line equivalent widths, those abundances were used while synthesizing the spectra. This way we could ascertain the contribution made by the contaminating lines of Fe-peak elements to the features of C I, O I etc. The parameters required to vary in order to get an agreement between theoretical and observed spectra were the abundance of C in the

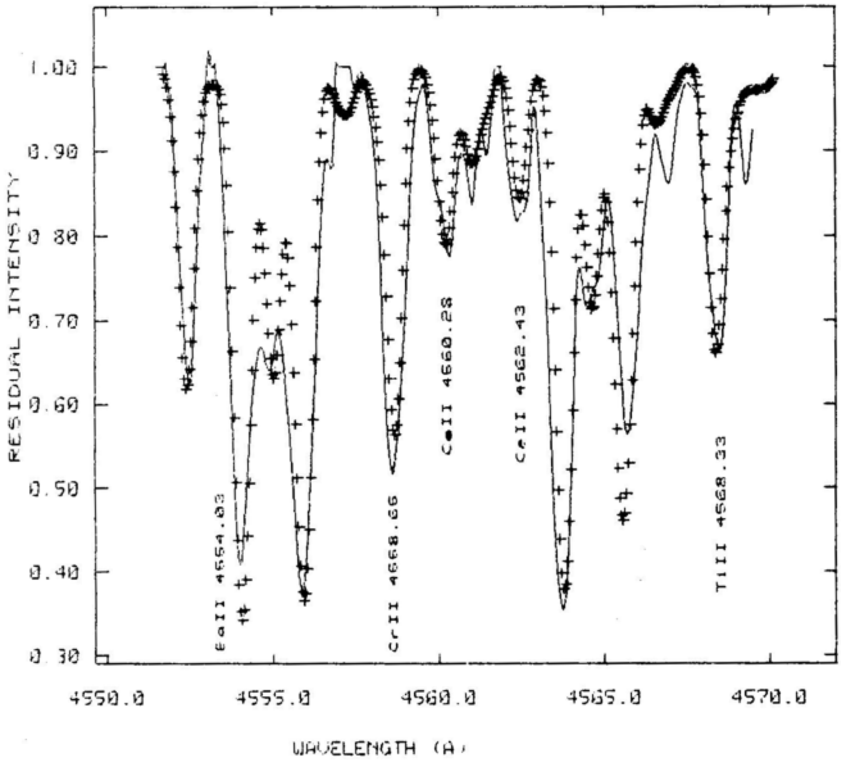

Figure 3. The agreement between the observed spectrum (continuous line) and synthesized spectra in the 4550–4570 Å region that includes Ba II and Ce II lines.

4770 Å region, O in the 6156 Å region, Ce in the 4560 Å region and the Ba in 4554 Å and 6141 Å regions.

The theoretical spectra were convolved with the instrumental profile (FWHM = 0.45 Å and shape assumed to be Gaussian) before comparing them with the observed ones. Figs 3, 4 and 5 show the agreement between the observed and computed spectra. Abundances of different elements as derived by us are presented in Table 2. It would appear from the figures that the synthesis do not fit the observed spectra very well. There could be many reasons for this. In particular, the presence of a few unidentified lines that could not be included in the synthesis calculations would explain the lack of agreement. The situation will hopefully improve when very extensive line identifications become available.

4. Results and error analysis

Errors arising due to uncertainties in line parameters like gf values and equivalent width measurements are usually random and cause line-to-line scatter. Standard errors are smaller when a large number of lines are employed for a given element. The standard deviation σ defined by $\sigma^2 = [\Sigma(x_i - x)^2/N - 1]$ was 0.18 dex for Fe where one could measure 40 lines. It leads to a value of 0.03 for the variance of the mean defined

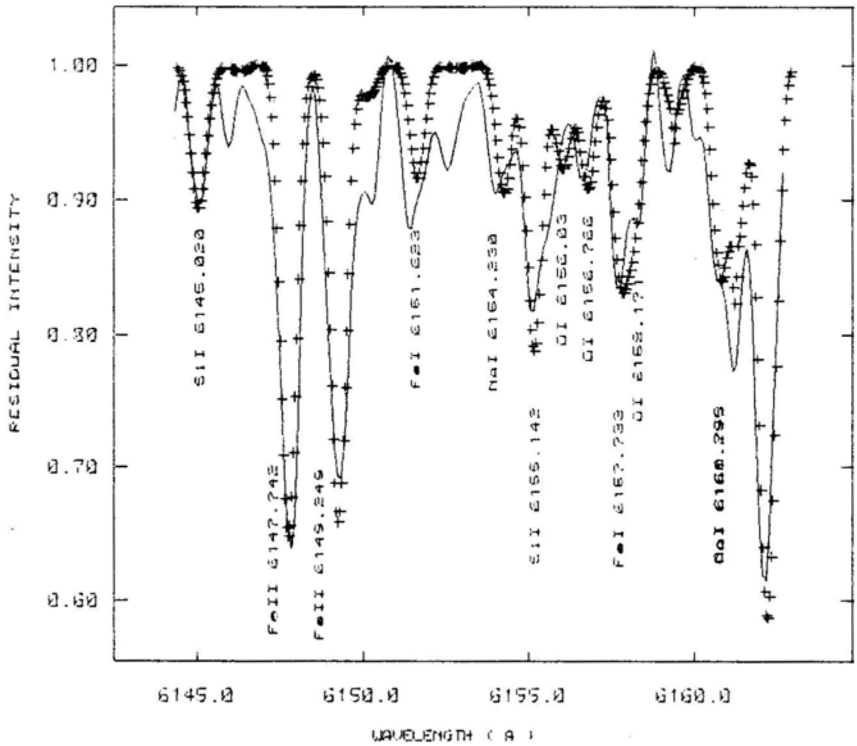

Figure 4. The agreement between the observed spectrum (continuous line) and synthesized spectra in the 6145–6162 Å region that contains O I lines.

by ($s = \sigma/N^{1/2}$). For other Fe-peak elements where we could use 10–20 lines, the Standard deviation is in the range of 0.20–0.25 dex.

The accuracy of the atmospheric parameters were estimated by computing a set of Fe I lines for pairs of models with the same gravity and microturbulence velocity but different temperatures, with the same temperature and gravity but different micro-turbulent velocities and with the same temperature and microturbulent velocity but different gravities. A comparison of the variations in the computed equivalent widths for the three cases with the accuracy of equivalent width measurements allowed us to estimate the accuracy of our atmospheric parameter determination. The uncertainty of the estimated T_{eff} is ± 200 K, of surface gravity log g ± 0.25 and of microturbulent velocity v_t ± 0.5 km s^{-1}. The cumulative effect of the uncertainties in atmospheric parameters is discussed in detail by Giridhar (1983). It is shown there that the errors in the derived abundances are not likely to be significantly larger than the errors estimated from the internal consistency check. The effects of NLTE on the determination of T_{eff} and log g were not explored.

It is interesting to note that we get almost a solar abundance for the element Fe. Si and Mn show minor enhancements of 0.3 dex whereas C shows a deficiency of 0.3 dex although the O abundance is almost solar. Ca shows a marginal deficiency of 0.2 dex but other Fe-peak elements show almost solar abundances. The s-process elements Ba and Ce are deficient by 0.5 dex and 0.3 dex respectively whereas only a marginal

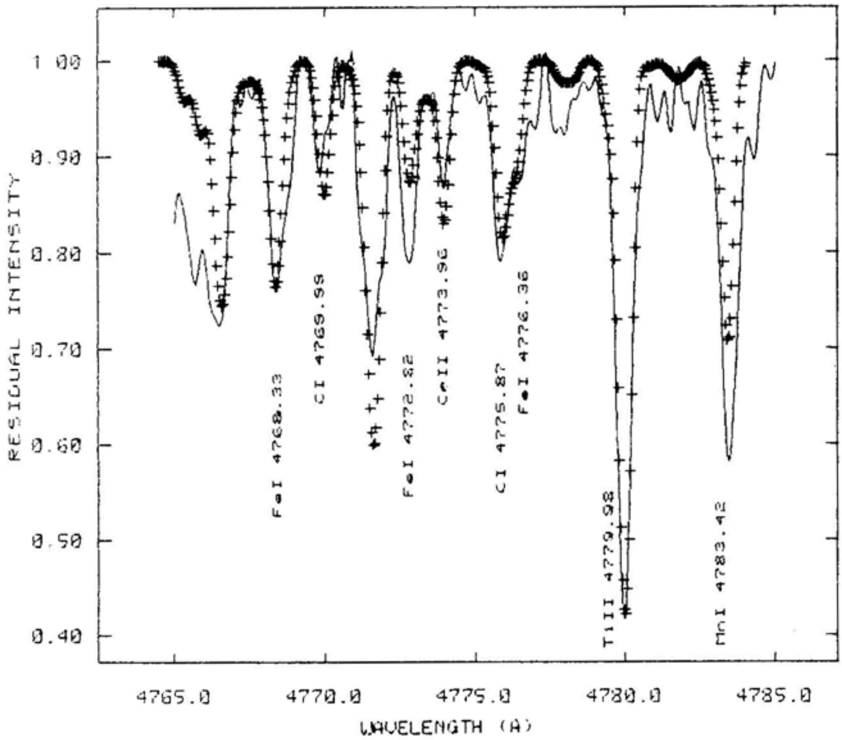

Figure 5. The agreement between the observed spectrum (continuous line) and synthesized spectra in the 4765–4785 Å region that contains C I lines.

Table 2. Abundances of elements with respect to solar value for RZ Vel.

Element	Z	Lines used Max	Min	RZ Vel $\phi=0.18$	$\phi=0.23$
C I	6	4		−0.31	
O I	8	3			0.05
A II	13	2		0.25	
Si I	14	8	7	0.28	0.30
S I	16	2		0.07	
Ca I	20	6	5	−0.20	−0.18
Ti I	22	5	3	0.20	0.15
Ti II	22	7	6	−0.04	−0.01
V I	23	3		0.23	
Cr I	24	5	4	−0.20	−0.10
Cr II	24	7	5	−0.10	0.05
Mn I	25	5		0.35	
Fe I	26	40	27	−0.04	−0.03
Fe II	26	15	10	−0.07	0.00
Co I	27	2		−0.13	
Ni I	28	3			−0.17
Y II	39	2		−0.15	
Ba II	56	2		−0.50	
Ce II	58	4		−0.30	

deficiency of 0.15 dex is shown by Y. On the whole the elemental abundances of RZ Vel are very similar to those of other classical cepheids in the solar neighbourhood (Luck & Lambert 1981; Giridhar 1983; Harris & Pilachowski 1984; Luck & Bond 1986).

5. Discussion

Though RZ Vel happens to be a bright southern cepheid, it is surprising that not much spectroscopic work has been done for this star. Light curves in the UBV system are given by Mitchell *et al.* (1964) and Madore (1975). The colour excess was determined by Dean, Warren & Cousins (1978). Since it is believed to be a member of Vela OB1, it was used in the calibration of the P–L–C relation by Caldwell (1983). Turner (1979) attributed the membership of Vel OB1 association to RZ Vel. It was based upon the spatial coincidence, reasonable agreement in colour excess and in evolutionary status with association members. Also the observed radial velocity of RZ Vel agrees very well with the OB stars of Vel OB1. The distance modulus for the association according to Turner (1979) is 11.23 mag and were the membership accepted, this would lead to a mean absolute magnitude $\langle M_v \rangle$ around – 5.12 which is in excellent agreement with $\langle M_v \rangle = -5.09$ derived using the P–L relationship of Sandage & Tammann (1968).

Eggen (1982) on the other hand did a photometric survey of the stars in Vela associations using a modified version of the Strömgren photometric system and ascribed the membership of the Vela OB2 association to RZ Vel. Though Eggen (1982) gives a very different distance modulus (9.5 mag) for Vel OB1, the distance modulus for Vela OB2 considered 11.3 mag by him leads to almost the same value of $\langle M_v \rangle$ for RZ Vel as that of Turner (1979).

However, Eggen (1982) estimated a very high metallicity for RZ Vel and other two cepheids belonging to the same OB association, using the metallicity index M1 (refer to Fig. 14 of Eggen (1982) which shows the loci for the stars of different metallicity range in the $M1_0 - (R - I)_0$ plane). Although we have not yet encountered a super metal-rich classical cepheid in the solar neighbourhood, one could not rule out the possibility of finding one. If there is some local enrichment of ISM due to supernova ejecta or from the ejecta of other massive evolved stars then the young cepheids born out of such an ISM would reflect the enrichment in their atmospheres. On the other hand, our spectroscopic investigation does not indicate a high metallicity for RZ Vel.

Using the period-age relationship of Effremov (1978) we estimated the age of RZ Vel at about 1.8×10^7 yr. Turner (1979) has estimated the age of Vela OB1 association members at around 2×10^7 yr. The age of the supernova remnant Vela X is estimated at around 1.3×10^4 yr by Gorenstein (1974) from X-ray observations. It is therefore highly unlikely that the ISM out of which the Vela OB1 association and RZ Vel are formed could have been metal enriched by the supernova remnant that happens to be occupying the same spatial direction.

It is well known that the photometric indices do not give metallicity as accurately as one would derive using spectroscopic means. In the case of the metallicity index M1 of Eggen (1982) it was pointed out by Feast (1987) that M1 and [M1] are dependent upon the $(b - y)$ colour and for cepheids the M1 and [M1] vary over the pulsation cycle in phase with $(b - y)$. It is also shown in Fig. 2 of Feast (1987) that the mean [M1] of Eggen's data correlates strongly with $\langle B_0 \rangle - \langle V_0 \rangle$ with a slope of 0.68. As a result, the M1 or [M1] indices of Eggen (1982) are not reliable indicators of metallieity. It is necessary to have a calibration of the M1 index in terms of [Fe/H] that will take into consideration the influence of the $(b - y)$ term.

Our present analysis shows that the metal abundances of the southern cepheid RZ Vel are very similar to those of the other classical cepheids. A mild deficiency of C and an almost solar abundance of O that could be caused by the first dredge-up have also been reported in other cepheids like 1 Car, SV Vul, ζ Gem by Luck & Lambert (1985). Hence RZ Vel is no different in evolutionary status from other cepheids of the solar neighbourhood.

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