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SV Vulpeculae: A first crossing Cepheid?*

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Abstract. We have undertaken a search for Cepheid variables which are crossing the instability strip for the first time. Such stars have finished their main sequence evolution and are moving through the HR diagram toward the red giant region. This evolutionary time interval is quite short when compared with the following stages of the core helium burning. Therefore, the number of the Cepheids which are crossing the instability strip for the first time should be at most several percent of the total number of Cepheids. The signature of a first crossing Cepheid is that its surface abundances should reflect its original composition. Using high quality spectral material obtained for a significant number of the Cepheids and determining consistent abundances throughout the sample, we have discovered one star, SV Vul, which can be considered a first crossing Cepheid.

Key words. stars: variable: Cepheids – stars: abundances

1. Introduction

When an intermediate mass star evolves off the main sequence it moves through the HR diagram to the red giant region crossing on its way the Cepheid instability strip. Having reached the red giant region, the star ignites core helium burning which rapidly changes its interior structure forcing it to shift within the HR diagram back towards hotter regions. After core helium exhaustion, the star again increases its radius and lowers the surface temperature while traveling to the red giant region for the second time. In the HR diagram such changes of stellar parameters are referred to as "blue loops". For stars of $5{-}12\ M_\odot$ the blue loops intersect the Cepheid instability strip. The helium burning phase is sufficiently long that the bulk of Cepheids observed at any one epoch are most probably core helium burning stars performing their blue loops. However, among the core helium burning Cepheids there should exist Cepheids which are crossing the instability strip for the first time. The time from the Main Sequence to the red giant region is quite short (about 20 times shorter than the helium core burning phase). Therefore, one can estimate that among the several hundreds of Cepheids known in the Galaxy, there should exist only several tens of stars crossing the instability strip for the first time.

There is no clear photometric criterion to distinguish between the ordinary Cepheids and those crossing the instability strip for the first time. The major problem with a photometric determination is that it is difficult to confidently assign the direction of evolution within the HR diagram for an individual Cepheid (i.e., to distinguish between, say, a first crossing Cepheid, and one in a core helium burning phase and therefore crossing the instability strip for the second or even third time). Successive passages of the instability strip by an individual star cross at ever higher luminosities but stars of higher mass also cross at higher luminosity so there is a further confusion related to the uncertain mass of any single object.

Cepheids crossing the instability strip for the first time should show their original surface composition, i.e., the first dredge-up has yet to occur. The criterion for finding such an object is thus to find one whose composition does not reflect the expected changes of the first dredge-up. For stars of intermediate mass the first dredge-up brings incomplete CNO-cycle processed material to the stellar surface. Upon being mixed with atmospheric gas, this

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[*] Based on the spectra collected with the 2.1−m telescope of McDonald Observatory and 2.1−m Kitt Peak National Observatory telescope.

additional processed material modifies the initial atmospheric abundances of the CNO elements. In particular, carbon becomes deficient relative to its initial abundance, nitrogen overabundant, while oxygen should remain practically unchanged. The underabundance of carbon in F−G supergiants was first demonstrated by Luck (1978) and subsequent papers (Luck & Lambert 1981, 1985, 1992; Luck 1994; Luck & Wepfer 1995). The general conclusion of all of these papers is that the intermediate mass stars are carbon deficient at about [C/H] = −0.3 and nitrogen enhanced at about [N/H] = +0.3. These results later were confirmed in the works of Andrievsky et al. (1996), Kovtyukh et al. (1996), Andrievsky & Kovtyukh (1996) for Cepheids and non-variable supergiants.

Thus, if we discover a Cepheid having (solar) normal abundances of carbon and/or nitrogen, it can be considered as a sign that this Cepheid is crossing the instability strip for the first time. The limiting factor in the interpretation is the lack of knowledge of initial abundances and of any processes which might alter the surface abundances while on the Main Sequence.

Other possible evolutionary status indicators are the abundance of Na which appears to be enhanced in post-first dredge-up intermediate mass stars (Sasselov 1986; Luck 1994; Denissenkov 1993a, 1993b, 1994). Additionally, some information may be derived from the presence/abundance of lithium but the implications here are not straight forward given the extreme sensitivity of the surface Li content to mass loss while the star is on the main sequence (for a first crossing star; the relevant time marker is the first dredge-up for a core helium burning star).

For low-mass stars this problem was investigated by Vanture & Wallerstein (1999), who tried to search for the cool giants situated in the Hertzsprung gap. Barbuy et al. (1996) detected two F supergiants that seem to show no effects of the first dredge-up; that is, they have solar carbon and nitrogen abundances. This indicates that they are probably in the first crossing phase. No Cepheid studied to date has abundances which would confidently identify it as crossing the instability strip for the first time.

2. Search strategy and observations

To search for first crossing Cepheids we have analyzed the spectra of a large number of Cepheids (50 stars) which are at our disposal (complete results for all the program stars of the sample will be published elsewhere). The spectra reduction procedure is described, for example, in Kovtyukh & Andrievsky (1999). We have initially concentrated only on the determination of the carbon, oxygen, sodium, and iron abundances for our sample. For SV Vul we have supplemented our survey data with additional spectra to allow a determination of the nitrogen abundance. As a result of the search, one star − SV Vul has been found to be a carbon/nitrogen normal Cepheid. Below we give a description of the spectroscopic material for this star.

Table 1. Observations.

Spectrum	HJD 24...	Phase	Telescope
1	48876.62947	0.669	KPNO 2.1 m
2	48878.76771	0.717	KPNO 2.1 m
3	49981.67704	0.237	KPNO 2.1 m
4	49982.71400	0.260	KPNO 2.1 m
5	49983.66534	0.282	KPNO 2.1 m
6	49984.66494	0.304	KPNO 2.1 m
7	49985.69595	0.327	KPNO 2.1 m
8	49986.66211	0.348	KPNO 2.1 m
9	50379.58714	0.085	McDonald 2.1 m
10	50381.55138	0.129	McDonald 2.1 m
11	50382.56326	0.151	McDonald 2.1 m
12	50383.57136	0.174	McDonald 2.1 m
13	50672.75472	0.604	McDonald 2.1 m
14	50674.77562	0.649	McDonald 2.1 m
15	50675.75208	0.671	McDonald 2.1 m
16	50677.79466	0.716	McDonald 2.1 m
17	50738.69196	0.070	McDonald 2.1 m
18	51058.75536	0.188	McDonald 2.1 m
19	51094.73986	0.988	McDonald 2.1 m
20	51096.69223	0.031	McDonald 2.1 m
21	51098.76320	0.077	McDonald 2.1 m
22	51473.62697	0.414	McDonald 2.1 m
23	51473.64877	0.414	McDonald 2.1 m

Phases were calculated using Berdnikov & Ignatova (2000) data.

Multiphase observations of 50 Cepheids including SV Vul (15 spectra) were acquired at McDonald Observatory using the Struve 2.1−m reflector and the Sandiford echelle spectrograph. The nominal resolution of this data is 60 000 with a spectral range of about 1000–1200 Å. For this data the signal-to-noise ratio is well in excess of 100. The echelle orders were extracted using standard IRAF procedures. Scattered light was removed by a surface fit to points midway between order centers. Regions on the CCD disturbed by internal reflections in the spectrograph are replaced by a smooth pseudo-spectrum before background subtraction.

Observations were also carried out at Kitt Peak National Observatory (KPNO) with the 2.1 m coudé-feed telescope. Eight high-resolution spectra (each of them three co-added spectra, resolving power $R \approx 80\,000$, $S/N \approx 150$) were taken in the spectral region 5600–7800 Å (25 orders). The KPNO spectra of SV Vul were initially analysed by Fry & Carney (1997) for the determination of the iron content. Detailed description of these spectra and their preliminary reduction can be found in that work. Additional information concerning the spectral material is presented in Table 1.

Further work with the spectra (continuum level, wavelength calibration, equivalent width measurements, etc) was performed using the IBM/PC compatible DECH20 package (Galazutdinov 1992). Equivalent widths of about 3400 lines were measured from the program spectra at each phase. Some lines were removed after preliminary

Table 2. Atmospheric parameters of SV Vul.

Spectrum	Phase	$T_{\rm eff}$, K	σ, K	N	σ(of mean), K	log g	$V_{\rm t}$, km s^{-1}
1	0.669	4880	61	28	11.5	1.0	5.0
2	0.717	4883	53	30	9.6	1.0	5.0
3	0.237	5314	64	30	11.7	0.7	4.9
4	0.260	5274	61	31	11.0	0.7	4.7
5	0.282	5209	44	29	8.3	0.7	4.7
6	0.304	5188	61	30	11.2	0.6	4.6
7	0.327	5155	57	30	10.3	0.5	4.5
8	0.348	5120	58	30	10.6	0.5	4.5
9	0.085	5805	113	24	23.1	1.2	5.8
10	0.129	5611	107	23	22.3	0.95	5.3
11	0.151	5548	77	25	15.4	0.95	5.1
12	0.174	5432	75	24	15.3	0.8	5.0
13	0.604	4896	51	20	11.4	1.0	5.0
14	0.649	4876	59	21	12.8	1.0	5.0
15	0.671	4873	71	23	14.8	1.0	5.0
16	0.716	4861	92	24	18.7	1.0	5.0
17	0.070	5856	91	26	17.8	1.2	5.9
18	0.188	5398	75	27	14.4	0.8	5.0
19	0.988	6110	202	18	47.5	1.6	6.8
20	0.031	5977	146	21	31.8	1.4	6.2
21	0.077	5755	126	21	27.6	1.05	5.6
22	0.414	5005	60	27	11.6	0.5	4.8
23	0.414	4995	75	20	16.9	0.5	4.8

N – the number of used spectroscopic criteria.

consideration with the final list containing in excess of 3200 lines. For a significant number of the lines we have two estimates of the equivalent width from adjacent orders. In all cases, the differences between independent estimates were rather small (less than 7%). In the abundance analysis we did not use lines having $W \geq 165$ mÅ (due to inadequate modeling in the top of the stellar photosphere).

At some pulsational phases the observed spectra are characterized by asymmetric line profiles (phases 0.98–0.10 and 0.40–0.70). The line asymmetries noted in SV Vul are due to macroscopic phenomena in the photosphere. Such motions affect the line profile but do not alter the equivalent width. Therefore, the asymmetries, while reflecting deviations from a pure equilibrium situation, should not have a major influence on the analysis. In the cases where the SV Vul lines are asymmetric we have determined the equivalent widths using an "equivalent width – line depth" relation (the method is described in Luck et al. 2000 in relation to a similar multiphase spectroscopic analysis of the classical Cepheid U Sgr).

3. Method of analysis and results

The effective temperature for SV Vul at each pulsational phase was determined using the new spectroscopic method developed by Kovtyukh & Gorlova (2000). The method is based on the relation between the effective temperature of a yellow supergiant and the depth ratios for selected spectral lines.

The gravity and microturbulence values were found using a modified method of spectroscopic analysis recently proposed by Kovtyukh & Andrievsky (1999). In this method the microturbulence is determined from Fe II lines (instead of Fe I lines, as used in "standard" abundance analyses). The gravity is determined by forcing the equality of the total iron abundance from both Fe I and Fe II. The usual case with this method is that the iron abundance determined from Fe I shows a strong dependence on equivalent width so we take as the proper iron abundance the extrapolated total iron abundance at zero equivalent width.

Atmosphere parameters are presented in Table 2. In Figs. 1–3 we illustrate the behavior of $T_{\rm eff}$, log g and $V_{\rm t}$ with a pulsational phase. In Fig. 1 we also plotted similarly phased $(b-y)$ indices (Kiss 1998) along with our data on effective temperature. As one can see, the temperature behavior is consistent with the photometry. The total range in temperature implied by the $(b-y)$ data ($\delta T_{\rm eff} \approx 1100$ K, Bell & Gustafsson 1978) is consistent with the determined effective temperature range. The implied $E(B-V)$ obtained by comparison of the determined effective temperatures with the photometry is somewhat larger than the value obtained by Bersier (1996): 0.68 versus 0.58.

In Fig. 2 which gives the variation of the gravity as a function of phase we have also included the expected variation of the effective gravity as calculated using the mass, expected radius and atmospheric acceleration. The dynamical portion of the gravity has been found as $\gamma * {\rm d}V/{\rm d}t$

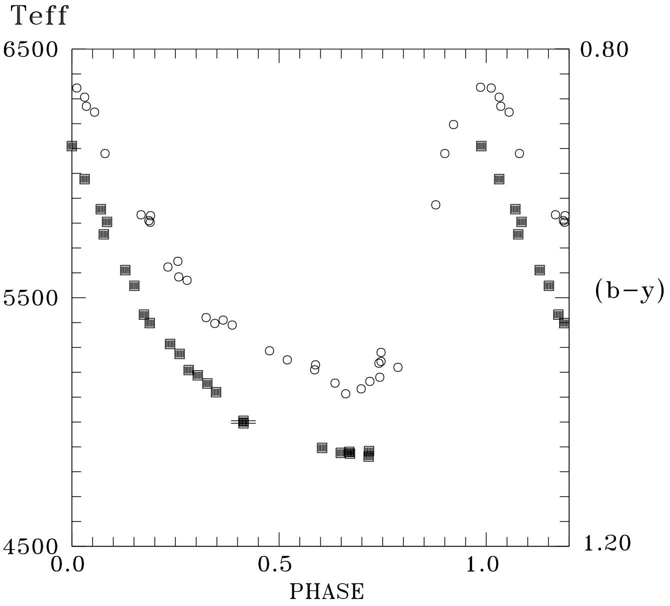

Fig. 1. SV Vul effective temperature variation through the pulsational cycle (*filled squares*). The variation of $(b-y)$ index is also shown (*open circles*).

($\gamma = 1.4$ is the projection factor). The radial velocity curve was taken from Bersier et al. (1994). The physical gravity component; i.e. GM/R^2, was calculated for 12 $M_{\odot}$ which was obtained from the period – evolutionary mass relation of Gieren (1989). The radius variation was found using $T_{\rm eff}$, the bolometric correction (depending on the temperature it varies from –0.290 to +0.066), and M_v (using P–M_v relation of Gieren et al. 1998). Full agreement between the spectroscopic $\log g$ and $\log(g_{\rm phys} + g_{\rm dyn})$ is not achieved, but the difference is not large. In the vicinity of the gravity maximum and minimum the difference is about 0.2 dex with the theoretical calculation undershooting the spectroscopic value in both cases. The agreement itself depends upon several factors: mass of the star, amplitude of radial velocity, and does the star fit the P–M_v relation. All these factors are uncertain to some extent and need further investigation. What can be stated at this point is that qualitatively both the curves are similar.

For the LTE abundance analysis we used the WIDTH9 code of Kurucz. The atmosphere models were also selected from Kurucz's grid. The list of the lines and oscillator strengths are those of Kovtyukh & Andrievsky (1999). Derived elemental abundances (mean values from all the investigated spectra) for SV Vul are given in Table 3. Note, that CNO and Na abundances resulting from several spectra taken at minimum light ($T_{\rm eff}$ less than 4900 K) were excluded from the calculation of averaged values (the permitted CNO lines are exceedingly weak and unreliable due to increasing blending while the Na lines are too strong). The list of the CNO and Na lines used in the present analysis is given in the appendix.

For comparison, in Table 3 we also give the abundances determined for ordinary classical Cepheid δ Cep, which possesses diminished carbon and enhanced nitrogen abundances (Kovtyukh & Andrievsky 1999), and also for two long-period Cepheids (similar to SV Vul) T Mon (averaged abundances from four phases) and S Vul (three phases).

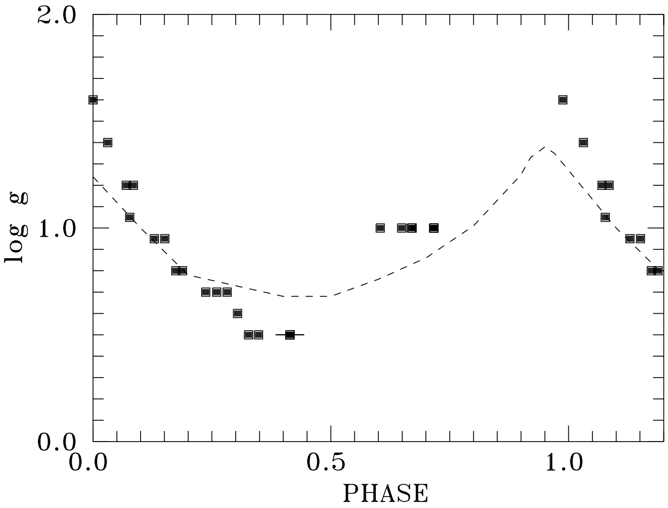

Fig. 2. Spectroscopic gravity variation.

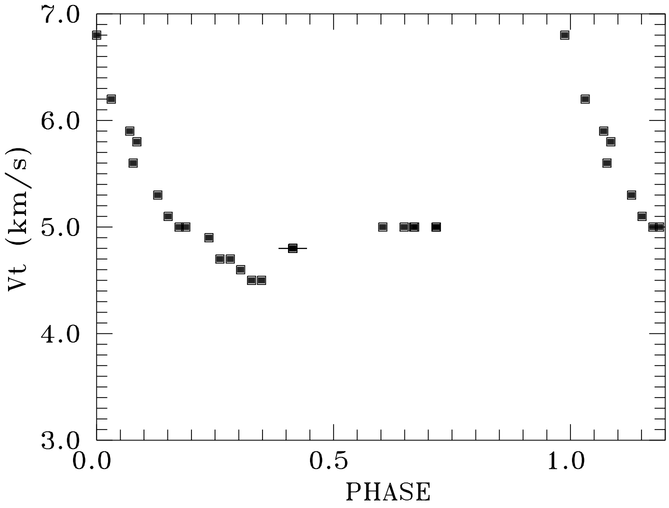

Fig. 3. Microturbulent velocity variation.

SV Vul has been previously analyzed by Luck & Lambert (1981, 1985, 1992). Comparing equivalent phases the atmospheric parameters are consistent as are the determined abundances.

4. Discussion

4.1. Properties of SV Vul

SV Vul is one of the longest period (≈45 days) classical Cepheids in the Galaxy. Gorynya et al. (1992), Bersier et al. (1994) and then Szabados (1996) and Kiss (1998) detected variations in the $\gamma-$velocity which are explained by the binarity of this star. From the O–C variation a period of about 10 000 days was determined.

From Geneva photometry Bersier et al. (1997) determined the radius of this star as $R = 155\ R_{\odot}$, while Laney & Stobie (1995) found that $R = 244\ R_{\odot}$.

Table 3. Elemental abundances for SV Vul (19 phases), δ Cep, T Mon and S Vul.

	SV Vul				δ Cep			T Mon			S Vul		
Ion	[M/H]	σ	N	(M/H)	[M/H]	σ	N	[M/H]	σ	N	[M/H]	σ	N
C I	+0.02	0.09	65	8.57	–0.21	0.12	32	–0.27	0.08	6	– 0.34	0.07	10
N I	+0.17	0.07	6	8.14	+0.43	0.10	12	–	–	–	–	–	–
O I	–0.01	0.12	26	8.86	+0.06	0.08	15	+0.08	0.10	7	– 0.40	–	1
Na I	+0.04	0.04	29	6.37	+0.16	0.04	18	+0.35	0.04	7	+0.21	0.10	3
Mg I	–0.10	0.12	6	7.48	–0.03	0.11	20	–	–	–	–	–	–
Al I	+0.13	0.07	31	6.60	+0.11	0.11	22	+0.10	0.15	4	+0.22	0.11	5
Si I	+0.06	0.11	234	7.61	+0.09	0.09	173	+0.13	0.08	31	– 0.03	0.14	29
Si II	+0.18	0.26	4	7.73	–0.01	0.13	13	–	–	–	–	–	–
S I	+0.16	0.22	30	7.37	+0.29	0.19	27	–	–	–	+0.22	0.14	5
Ca I	–0.04	0.11	58	6.32	–0.05	0.09	50	+0.09	0.19	12	– 0.04	0.11	5
Sc II	–	–	–	–	+0.08	0.10	33	–	–	–	–	–	–
Ti I	+0.02	0.19	189	5.04	+0.02	0.12	137	+0.05	0.15	23	+0.05	0.19	14
Ti II	+0.00	0.04	15	5.02	+0.05	–	7	+0.12	0.06	4	– 0.08	0.12	3
V I	–0.07	0.15	196	3.93	+0.00	0.13	116	+0.03	0.11	27	+0.08	0.15	17
V II	–0.13	0.08	23	3.87	–0.07	0.07	12	+0.00	0.01	4	– 0.18	0.04	3
Cr I	+0.00	0.20	80	5.67	+0.06	0.18	88	+0.30	0.18	6	+0.07	0.16	4
Cr II	+0.20	0.08	10	5.87	–	–	–	+0.22	0.02	3	+0.20	–	1
Mn I	–0.18	0.08	29	5.21	–0.05	0.12	28	–0.12	0.04	7	– 0.22	0.12	7
Fe I	+0.03	0.10	1422	7.53	0.06	0.10	994	+0.13	0.08	252	– 0.02	0.07	139
Fe II	+0.06	0.09	177	7.56	0.09	0.09	90	+0.12	0.06	39	– 0.04	0.05	15
Co I	–0.13	0.09	77	4.79	–0.10	0.12	60	–0.03	0.04	13	– 0.22	0.07	7
Ni I	+0.00	0.10	336	6.25	–0.01	0.10	311	+0.05	0.07	63	+0.02	0.08	33
Cu I	–0.16	0.14	11	4.05	0.06	0.05	13	–	–	–	+0.03	0.34	2
Zn I	+0.22	0.11	8	4.82	0.16	–	6	+0.34	0.04	4	–	–	–
Y I	+0.38	0.14	6	2.62	–	–	–	+0.64	0.08	3	–	–	–
Y II	+0.26	0.10	24	2.50	+0.29	0.03	14	–	–	–	+0.22	0.09	4
Zr II	–0.08	0.08	16	2.52	+0.00	0.11	8	+0.04	0.06	4	– 0.06	0.05	3
La II	+0.20	0.09	17	1.42	+0.18	0.14	9	+0.30	0.03	4	+0.18	–	1
Ce II	–0.13	0.10	24	1.42	+0.07	0.16	12	+0.02	0.06	7	– 0.25	0.08	4
Nd II	+0.05	0.15	50	1.55	–0.02	0.03	13	+0.22	0.18		+0.15	0.15	9
Eu II	+0.04	0.08	33	0.55	+0.07	0.16	14	+0.15	0.12	7	+0.02	0.13	5
Gd II	+0.03	0.07	8	1.15	–	–	–	–	–	–	– 0.01	0.03	3

N – is the total number of the line used in analysis.

Benz & Mayor (1982) derived an upper limit for the projected rotational velocity of SV Vul $v \sin i$ of less than 14 km s^{-1}. They also estimated the turbulent motion velocity as being equal to 18 km s^{-1}. Luck & Lambert (1981, 1985, 1992) determined from synthetic spectrum matches a macroturbulent velocity of 12 km s^{-1}. The line broadening in Cepheid spectra is likely due to turbulence rather than stellar rotation (Kraft 1966). Our spectral material for SV Vul indicates that the lines in its spectrum are broadened at the levels determined previously.

4.2. SV Vul as a first crossing Cepheid

The abundances of carbon and nitrogen determined for SV Vul, being close to the solar values, indicate that this star has never been through the first dredge-up. Otherwise, we should expect the abundances of these elements to have been significantly altered by the dredge-up. Of course, there exists the alternative possibility that the precursor of SV Vul was a C-rich (say, [C/H] $\approx +0.2$ dex) N-poor star, and after the first dredge-up the Cepheid with the currently observed abundances was created from that progenitor. Nevertheless, such a supposition meets some difficulties. The primary difficulty encountered is that SV Vul besides being essentially solar normal in C and N (as well as Fe), is also essentially solar normal in Na whereas a processed (through the first giant branch) intermediate mass star should show an enhanced Na content (as do the remainder of the program stars). If SV Vul is a star that has been through the first dredge-up then its precursor would have been C rich, N and Na poor all at about the 0.2 dex level relative to solar values. While not impossible, it does appear unlikely given that the overall metallicity of the star is solar and so our preferred interpretation of SV Vul is that it is a first crossing star.

To provide some quantitative criteria, we constructed several histograms (Figs. 4–6), showing the distribution of relative abundances of carbon, oxygen and sodium in our sample of classical Cepheids (the McDonald Observatory high resolution spectra for 50 stars of which SV Vul is one).

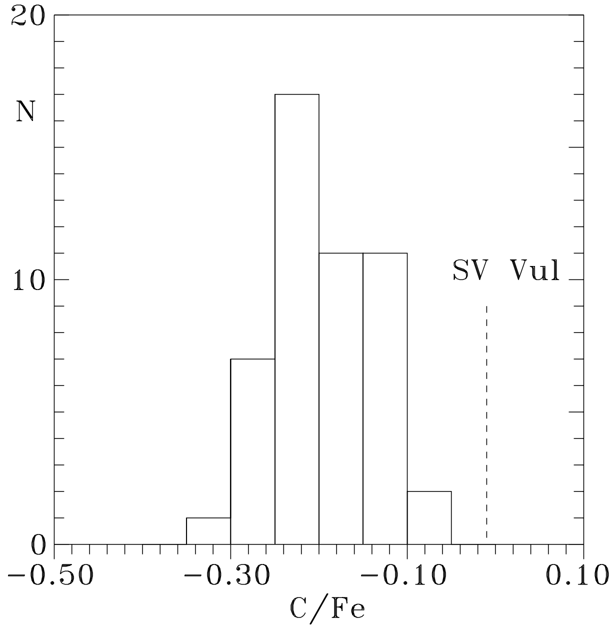

Fig. 4. [C/Fe] histogram. The position of SV Vul is indicated by dashed line.

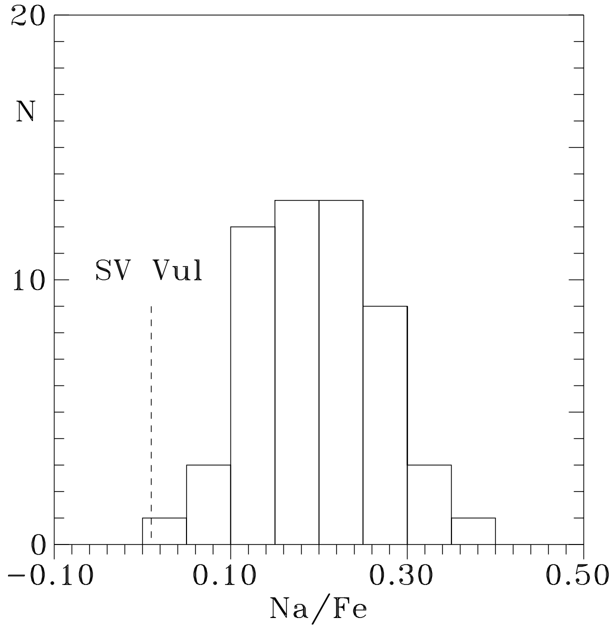

Fig. 5. [Na/Fe] histogram.

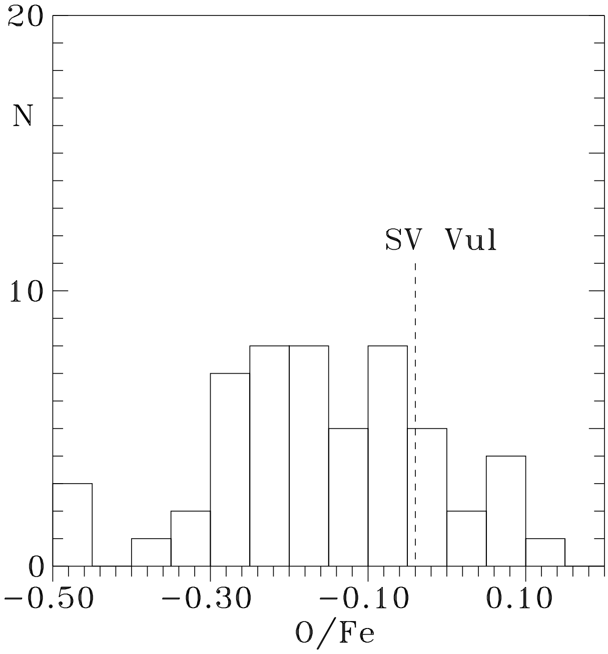

Fig. 6. [O/Fe] histogram.

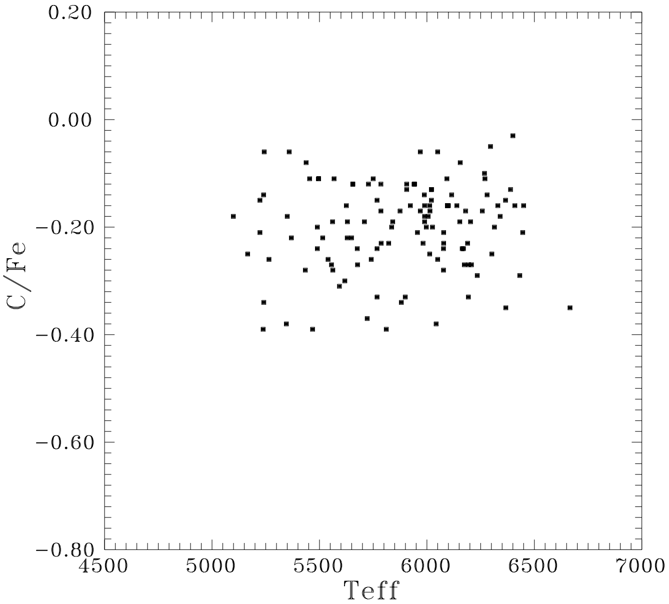

Fig. 7. [C/Fe] vs. effective temperature for all investigated Cepheids.

All these Cepheids were investigated in the same manner as SV Vul. In Figs. 7,8 we plotted the carbon relative-to-iron abundance vs. T_{eff} and $\log g$ for a sample of investigated Cepheids. No obvious dependence of the derived carbon abundance upon the atmospheric parameters can be seen. Our conclusion is that the derived abundances in SV Vul are not due to incorrect atmospheric parameters but indicate that SV Vul, unlike the remaining stars, has not undergone the first dredge-up.

As one can see from Fig. 4, the carbon abundance in SV Vul is clearly higher than in usual Cepheids, which are supposed to have already experienced at least the first dredge-up. At the same time, the sodium abundance is obviously lower than in other Cepheids, despite that SV Vul being a long-period (and therefore massive) Cepheid might be expected to have a remarkable sodium overabundance. Oxygen is not predicted to be significantly altered after the mixing of the atmospheric gas with the material processed in the incomplete CNO-cycle. In fact, the relative oxygen abundance in SV Vul does not differ from that of other Cepheids. Because the observed region in McDonald spectra of the program Cepheids is limited to blueward of 6900 Å, we were not able to construct the histogram for nitrogen abundance. It should be

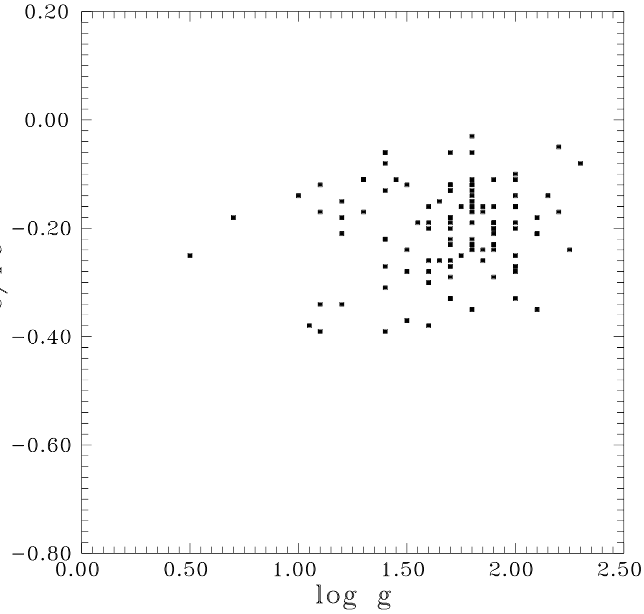

Fig. 8. Same as Fig. 7, but for the gravity.

also noted that abundances of carbon, oxygen and sodium in SV Vul are also in contrast with those obtained for two long-period and therefore massive Cepheids T Mon and S Vul (see Table 3).

We have also looked for Li in the spectrum of SV Vul and it is not detected at any phase. If Li had been present then this would have provided additional support for our interpretation. However, Li is extremely sensitive to mass loss (Li survives only in the outer 1% by mass of B stars' Cepheid precursors) and so the lack of Li says little either way about the evolutionary status of SV Vul. As an aside, to our knowledge no classical Cepheid shows any indication of the presence of Li. This is curious as a number of non-variable supergiants do show an observable Li content (Luck 1977).

Summarizing, with its peculiar abundances of carbon, nitrogen and sodium (compared with ordinary Cepheids) SV Vul can be considered as the Cepheid which is presently crossing the instability strip for the first time.

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Appendix A:

Table A.1. List of the measured CNO and Na lines for SV Vul KPNO spectra: oscillator strengths, potentials (in eV) and equivalent widths (in mÅ).

λ	Ion	$\log gf$	ϵ	1	2	3	4	5	6	7	8
5800.59	C I	–2.31	7.950	–	–	–	27.0	–	–	–	–
6001.12	C I	–1.88	8.640	–	–	–	15.0	14.0	–	–	13.0
6010.68	C I	–1.87	8.639	–	–	25.0	25.0	–	–	–	–
6014.83	C I	–1.66	8.639	–	–	31.0	22.0	22.0	21.0	21.0	16.0
6587.61	C I	–1.13	8.539	29.0	–	76.0	73.0	71.0	69.0	62.0	60.0
6655.51	C I	–1.79	8.539	13.5	15.0	26.0	28.0	29.0	26.0	26.0	25.0
6671.85	C I	–1.66	8.850	–	–	–	–	31.0	–	–	–
6688.79	C I	–2.09	8.849	–	–	11.0	12.0	12.0	–	14.0	13.0
7113.18	C I	–.79	8.649	98.0	82.5	–	–	–	–	–	–
7115.19	C I	–.72	8.639	98.0	–	–	–	–	–	–	–
7132.11	C I	–1.73	8.649	32.0	38.0	–	–	–	–	–	–
7837.11	C I	–1.44	8.849	27.0	22.0	–	–	–	–	–	–
7468.30	N I	.05	10.339	–	–	31.0	33.0	31.0	26.0	25.0	29.0
8629.16	N I	.31	10.689	68.0	80.0	–	–	–	–	–	–
6156.77	O I	–.27	10.739	–	–	27.0	24.0	27.0	–	–	–
6300.30	O I	–9.83	.000	–	–	101.0	100.0	113.0	–	–	–
6363.78	O I	–10.20	.020	–	–	69.0	73.0	70.0	73.0	77.0	73.0
7771.95	O I	.18	9.149	165.0	173.0	–	–	–	–	–	–
7774.17	O I	.17	9.149	158.0	182.0	–	–	–	–	–	–
7775.39	O I	–.15	9.149	113.0	115.0	–	–	–	–	–	–
5682.65	Na I	–.52	2.100	–	–	194.0	–	188.0	191.0	–	–
5688.22	Na I	–.45	2.100	–	–	249.0	–	–	–	–	–
6154.23	Na I	–1.54	2.100	103.0	105.0	70.0	77.0	80.0	80.0	74.0	88.0
6160.75	Na I	–1.22	2.100	–	–	117.0	118.0	122.0	119.0	120.0	122.0

Table A.2. The same as Table 1, but for McDonald spectra.

λ	Ion	$\log gf$	ϵ	9	10	11	12	13	14	15	16	17
6001.12	C I	–1.88	8.640	25.9	18.8	–	–	21.7	–	–	–	–
6010.68	C I	–1.87	8.639	25.6	26.9	25.6	22.3	21.7	23.3	–	21.7	31.9
6014.83	C I	–1.66	8.639	37.7	31.3	32.9	22.3	9.8	–	–	–	33.4
6587.61	C I	–1.13	8.539	–	–	–	–	40.5	–	–	36.2	103.7
6655.51	C I	–1.79	8.539	26.6	31.2	25.6	18.9	–	–	14.3	–	31.7
6688.79	C I	–2.09	8.849	–	8.8	–	14.9	–	–	–	–	–
7113.18	C I	–.79	8.649	94.4	–	–	106.0	–	–	–	–	–
7115.19	C I	–.72	8.639	118.6	119.8	108.3	112.0	–	–	–	–	–
7116.99	C I	–.88	8.650	109.8	94.7	115.1	102.0	–	–	–	–	–
7119.67	C I	–1.01	8.640	–	–	–	91.0	–	–	–	–	–
7132.11	C I	–1.73	8.649	–	–	12.1	17.0	–	–	–	–	–
6156.77	O I	–.27	10.739	40.2	31.7	26.0	24.3	–	–	–	–	39.8
6363.78	O I	–10.20	.020	35.3	51.0	67.0	59.5	–	–	62.6	82.4	41.7
5688.22	Na I	–.45	2.100	–	–	–	–	358.0	–	–	–	–
6154.23	Na I	–1.54	2.100	57.5	57.2	62.0	67.0	103.4	102.7	106.0	96.6	58.1
6160.75	Na I	–1.22	2.100	87.9	85.7	93.8	92.2	–	–	–	–	81.0

Table A.2. continued.

λ	Ion	$\log gf$	ϵ	18	19	20	21	22	23
5800.59	C I	–2.31	7.950	36.0	–	–	–	–	–
6001.12	C I	–1.88	8.640	–	33.6	23.7	–	–	–
6010.68	C I	–1.87	8.639	33.0	24.2	24.9	20.0	–	–
6014.83	C I	–1.66	8.639	28.0	31.9	32.0	27.0	13.7	13.0
6587.61	C I	–1.13	8.539	87.0	128.1	103.4	109.0	48.0	52.0
6655.51	C I	–1.79	8.539	31.0	46.5	36.5	29.0	13.3	18.0
6671.85	C I	–1.66	8.850	–	–	–	32.0	–	–
6688.79	C I	–2.09	8.849	–	–	12.4	–	–	–
6156.77	O I	–.27	10.739	–	43.0	36.5	32.1	–	–
6363.78	O I	–10.20	.020	15.2	–	38.0	51.7	65.0	58.0
5682.65	Na I	–.52	2.100	–	–	–	–	230.0	215.0
5688.22	Na I	–.45	2.100	–	242.7	–	–	–	–
6154.23	Na I	–1.54	2.100	78.0	43.2	41.9	58.0	98.0	106.0
6160.75	Na I	–1.22	2.100	96.0	–	74.8	78.1	146.0	123.0