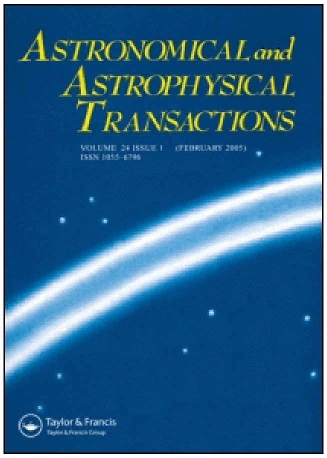

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Spectroscopy of selected pulsating stars: The anomalous variable V351 Cep

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Online Publication Date: 01 July 1995
To cite this Article: Galazutdinov, G. A. and Klochkova, V. G. (1995) 'Spectroscopy of selected pulsating stars: The anomalous variable V351 Cep', Astronomical & Astrophysical Transactions, 8:3, 227 - 237
To link to this article: DOI: 10.1080/10556799508203309
URL: http://dx.doi.org/10.1080/10556799508203309

Astronomical and Astrophysical Transactions, 1995,
Vol. 8, pp. 227-237
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SPECTROSCOPY OF SELECTED PULSATING STARS: THE ANOMALOUS VARIABLE V351 CEP

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(Received February 16, 1994)

The physical parameters: effective temperature T_{eff}, surface gravity $\log g$, microturbulent velocity ξt, abundances of 26 chemical elements, radial velocity V_r – were obtained for 5 phases of the variable star V351 Cep using CCD echelle spectra with spectral resolution $R = 25000$ in the region $\lambda\lambda$ 5100–8800 Å. The chemical composition of V351 Cep coincides within the errors with the solar composition and, except for the CNO elements, it coincides with the chemical composition of the young supergiant α Per. It is shown that the massive supergiant α Per has an essential overabundance of N and deficiency of C, O in comparison with the solar abundances, which is in good agreement with evolutionary status of α Per. At the same time, no considerable modifications of the CNO abundances for V351 Cep were found. It evidences for absence of dredge-up H-burning products to the surface of the star.

The luminosity of V351 Cep, $M_V = -3^m.0$, was obtained using the intensity of the infrared triplet OI (near 7774 Å). This value is not consistent with the luminosity obtained from the P–L relation.

The combination of the physical parameters of V351 Cep allows to classify V351 Cep as an anomalous cepheid.

KEY WORDS Stars: abundances – atmospheres of – cepheids – stars: individual: V351 Cep.

1 INTRODUCTION

The W Vir type pulsating stars are of special interest for investigations of late evolutionary stages of Population II stars. Usually classified by light curve shape, W Vir stars under more detailed consideration, prove to be a very inhomogeneous class of variable stars. The position of W Vir stars in the HR diagram and their physical characteristics lead to a suggestion that the BL Her subclass (with periods 2–6^d) are pre-AGB (asymptotic giant branch) stars, but the W Vir subclass

(P = 8–30^{d}) are post-AGB stars. This suggestion needs further tests including the study of chemical composition details. It is obvious that for understanding the nature of W Vir stars it is necessary to study both the metallicity and the details of the chemical abundance curve that are sensitive to the stellar population type and evolution stage (Li, CNO, metals synthesized by r- or s-processes).

Only two W Vir type stars in the galactic field: κ Pav with [Fe/H] = 0.0 (Luck and Bond, 1989) and AU Peg, [Fe/H] = 0.1 (Harris *et al.*, 1979), have been investigated by now using high resolution spectra and the method of model atmosphere. Wallerstein *et al.* (1979) studied the chemical composition of the short-period variable V553 Cen and derived the metallicity [Fe/H] = −0.7. For κ Pav, with the period $P = 9\overset{d}{.}1$ the heavy s-process elements were found to be deficient, but the short-period variables AU Peg and V553 Cen have overabundances of these heavy metals. An excess of s-process elements has been reported by Evans (1978) for two long-period Cepheids in the globular cluster ω Cen. Two Population II Cepheids in the galactic field, CC Lyr and ST Pup, have extremely weak metal and hydrogen lines but their chemical composition is not studied. Thus the necessity of investigation of chemical composition for W Vir stars is evident.

2 OBSERVATIONS

During the recent two years we have been carrying out the programme of spectroscopy of W Vir stars aiming at the study of variability of their main physical parameters ($T_{\rm eff}$, $\log g$, V_r) and at determination of peculiarities of chemical composition for these objects that have experienced a change of nuclear burning sources and a possible dredge-up of nucleosynthesis products to the surface.

The chemical composition of the atmospheres of variable stars is now being investigated using the grid of plane-parallel model atmospheres calculated in the hydrostatic equilibrium approximation. Therefore it is necessary to estimate the stability of the calculated abundances deriving them for various phases of the light curve. Such spectroscopic monitoring may also be useful for investigation of velocity fields in the atmospheres of selected W Vir stars. Hence it is evident that W Vir stars have to be observed at different phases of their light curves.

The programme is based on a selection from the General Catalogue of Variable Stars (Kholopov *et al.*, 1985) of stars that are noted as W Vir variables and are brighter than 12^{m}. All observations were carried out with the 6m telescope using the echelle spectrometer LYNX (Panchuk *et al.*, 1993) equipped with a CCD (530 × 580 pixels) (Borisenko *et al.*, 1991). The echelle grating having 37.5 lines mm^{-1} with blaze angle $\theta = 63\overset{\circ}{.}5$ was used; the first-order gratings of 300 or 200 lines mm^{-1} were operating as the crossdisperser. The registered spectral range was 5100–7200 Å in the first case and 5500–8800 Å in the second one. In both cases, 30–32 spectral orders were registered. The slit sizes were 0.6 x 2.7 arc sec. The spectral resolution was R = 25000. For wavelength calibration we used a $Th + Ar$ lamp and telluric spectrum lines that are well represented in this spectral region.

Table 1. The observed W Vir stars

Object	*M*	*m*	*P(d)*
RU Cam	$8\overset{m}{.}10$	$9\overset{m}{.}79$	$22\overset{d}{.}00$
TW Cap	9.95	11.28	8.61
BD Cas	10.84	11.21	3.65
IX Cas	11.19	11.77	9.15
V351 Cep	9.25	9.70	2.80
TX Del	8.84	9.54	6.16
BL Her	9.70	10.62	1.30
SW Tau	9.33	10.16	1.58
AL Vir	9.10	9.92	10.30
W Vir	9.46	10.75	17.27

In Table 1 we list W Vir type stars for which the CCD echelle spectra have already been obtained. Here m, M are the visual magnitudes for the minimum and maximum of the light curve, respectively; $P(d)$ is the period.

3 RESULTS OF THE ANALYSIS OF V351 CEP SPECTRA

In this section the results are presented for one object of the programme – V351 Cep (BD +56°2806, HD 239994). Fernie and Hube (1971) were the first to reveal that V351 Cep was located within the instability strip of the HR diagram. Later Percy (1975) determined that V351 Cep was a Cepheid with a period of about 3 days. Szabados (1976) derived a more accurate value, $P = 2\overset{d}{.}80591$. Erleksova (1978), using about 1200 observations during 1940–1975, concluded that V351 Cep was a W Vir type (BL Her subtype) star with increasing period $(\Delta P/P)_{100} = 0.001$, per 100 cycles.

V351 Cep remains poorly studied, and only Ferro (1984) estimated by photometric method the main physical parameters for this object: the effective temperature $T_{\rm eff}$ higher than 5900 K, the luminosity $M_V = -2\overset{m}{.}75$, the mass about 5 solar values. These parameters combined with the galactic latitude of V351 Cep, $b = 0°$, show that V351 Cep belongs to the galactic Population I. However, the presence of a hump on the descending branch of the light curve (Erleksova, 1978) contradicts such a conclusion.

From all obtained echelle spectra of V351 Cep, we selected for subsequent analysis only 5 spectra having S/N ratios which can ensure measurements of weak absorption lines with equivalent widths $W > 3$–5 mA (Figure 1). The observing data for the spectra are of the spectral order to 60–70 at its edges. given in Table 2. The S/N ratio varies from 100–120 at the center

As standards of the equivalent widths and radial velocities, we used the supergiant α Per (F51b), which is a member of the open cluster of the same name, and the main sequence star α CMi (F5IV), respectively.

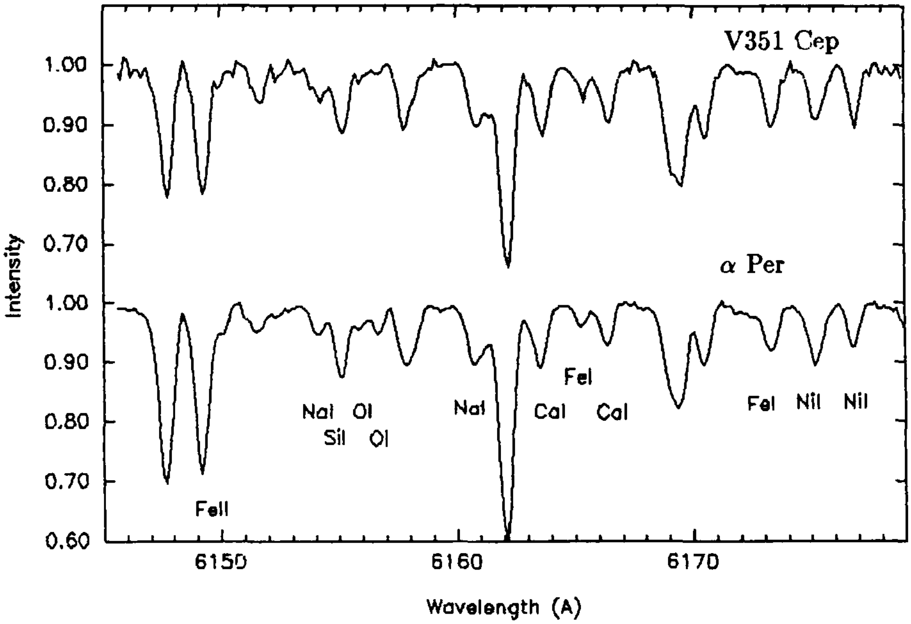

Figure 1 Spectral region around OI lines near 6156 Å for V351 Cep and α Per.

On each observing night we obtained double exposures (2×45 min or 2×30 min) for V351 Cep, which allows us to use the effective method of automatic removal of cosmic ray hits from CCD images.

4 IMAGE AND SPECTRA PROCESSING

The image processing and the following reductions of spectra were performed using IBM PC oriented original software (Galazutdinov, 1992). Background substraction, removal of cosmic ray hits, subsequent addition of images of double exposures and elimination of scattered light were performed at the first stage of processing spectra. A spectrum extraction procedure from the echelle format was performed using the optimal extraction algorithm (Horne 1984). The equivalent width measurements were performed using one of the three methods: direct integration, Gaussian approximation, or approximation by a triangle, depending on suitability for different lines.

5 DETERMINATION OF MODEL ATMOSPHERE PARAMETERS

To compute the chemical composition of V351 Cep, the WIDTH6 program and Kurucz's (1979) models of stellar atmospheres were used. The applicability of these models to W Vir stars, having extended unstable atmospheres, may be doubtful. However, there is a successful experience of the use of these models for spectra of Population I Cepheids and other supergiants (Luck and Bond, 1989; Spite *et al.*, 1989; Klochkova, 1991a; Klochkova and Panchuk, 1991). The chemical composition of a pulsating supergiant, derived by the model atmosphere method, was usually considered relative to the chemical composition of an ordinary supergiant with similar physical parameters. Such a comparison compensates for a part of methodical errors. Besides, it is important that only weak absorption lines ($W < 200$ mA), which are formed in deep atmospheric layers and are described by models more reliably, are selected for the abundance calculations. Spite *et al.* (1989) have shown that the use of the weak absorption lines in a spectral analysis reduces the non-LTE effects on a chemical abundance to the value $\Delta \lg \varepsilon < 0.11$ dex.

The data on atomic oscillator strengths $\log gf$ have been taken from Thevenin (1989, 1990). For light elements (CNO), the $\log gf$ values from Waelkens *et al.* (1991) have been applied.

The atmospheric parameters (effective temperature T_e, surface gravity $\log g$) have been derived by the traditional method taking advantage of the independence of FeI abundances on excitation potential of the used lines (see Figure 2) as well as of the ionization equilibrium for FeI/FeII.

The microturbulent velocity ξ_t has been derived for an imposed condition of there being no dependence of abundance (from FeI lines with $W < 200$ mA) upon equivalent width (see Figure 2). The accuracy of determination of Te is equal to ± 200 K, of $\log g$, to ± 0.2, and of ξ_t, to ± 0.3 km s^{-1}.

The hydrogen line H_α in the spectra of V351 Cep has no emission at any of the investigated phases of the light curve, and neither any variability of the H_α profile has been revealed. The latter fact is consistent with the data of Table 2: the atmospheric parameters are invariable for different phases within the accuracy of the method.

It is well known that for pulsating stars T_e – phase relation is observed. For V351 Cep no important T_e variability has been discovered, which is in good agreement with the very small amplitude of its light variations. Nevertheless, the abundance calculations were carried out separately for each phase with the parameters indicated in Table 2. Taking into account the error of the method, the same chemical composition (see Table 3) was, however, derived for all spectra available, which permits to average the abundance data for all phases in order to improve the reliability of the results. The averaged abundance values are given in Table 4 together with the chemical composition of the standard supergiant α Per and the solar chemical composition (Grevesse, 1993).

6 CHEMICAL COMPOSITION

As follows from Table 4, the abundances of iron peak elements for V351 Cep and for α Per are similar and approximately equal to solar values. At the same time, no marked variation of CNO abundances was revealed for V351 Cep, while for

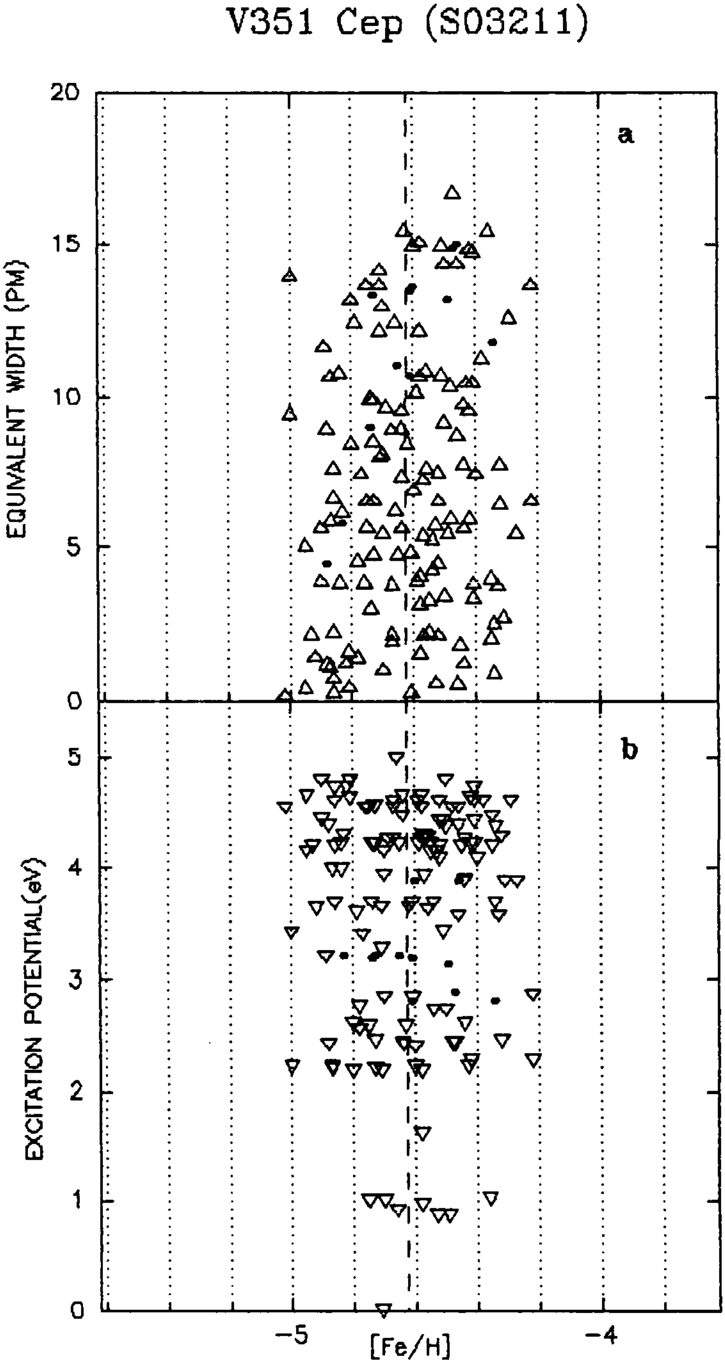

Figure 2 a) The iron abundance versus the equivalent width of the line ([FeI/H] – triangles, [FeII/H] – filled circles). b) The [Fe/H] value versus the excitation potential of the line (symbols as in 2a).

Table 2. Journal of observations and the atmospheric parameters for different spectra of V351 Cep

Sp	*JD=244...*	ϕ	$\lambda\lambda$ *(Å)*	*Te (K)*	$\log g$	ξt *(km* s^{-1}*)*
S03211	8851.576	0.71	5100–7200	6150	1.2	2.6
S03308	8853.506	0.38	5100–7200	5950	1.2	3.1
S03605	8857.516	0.78	5100–7200	6150	1.0	2.9
S04101	8999.113	0.14	5500–8800	6000	1.5	2.6
S06405	9203.373	0.30	5500–8800	6000	1.5	3.5

Table 3. The chemical abundance $\log\varepsilon(X) \pm \sigma$ in the atmosphere of V351 Cep for different phases. In the last column the typical number of the used lines is given

	$-\log\varepsilon(X)$					n
	φ = *0.14*	φ = *0.30*	φ = *0.38*	φ = *0.71*	φ = *0.78*	
C	3.20	3.60 ± .12	3.80	3.87		2
N		3.97 .07				2
O		2.99 .18	3.39			3
Na	5.63:	5.54 .08	5.54	5.13 .13	5.32 .21	3
Mg	4.70	4.66 .15	4.44 .11	4.26 .05	4.34 .06	3
Al	5.28	5.74 .15	5.31	5.17 .08	5.30 .05	3
Si	4.38 .11	4.44 .04	4.42 .05	4.42 .03	4.42 .04	14
Si^+		4.43	4.21	3.86	3.81	1
Ca	5.30 .09	5.67 .06	5.60 .05		5.52 .06	15
Sc^+	8.71 .06	9.00 .17	9.12 .05	8.83 .08	9.10 .05	7
Ti		7.22 .07	7.05 .07	7.34 .09	7.17 .14	6
Ti^+	7.23	7.37	7.12 .09	7.29 .10	7.32 .06	4
V	7.80 .12	7.32 .15	7.81 .09	8.01 .06	7.51 .08	6
V^+		8.30 .07		8.33	8.38	3
Cr	6.29 .06	6.29 .10	6.47 .05	6.50 .04	6.69 .09	13
Cr^+			6.53 .07	6.31 .10	6.53 .07	7
Mn	6.42 .25	6.77 .11	6.75 .06	6.58 .09		6
Fe	4.38 .02	4.65 .02	4.57 .01	4.62 .02	4.63 .02	120
Fe^+	4.46 .06	4.64 .05	4.59 .05	4.62 .05	4.67 .04	12
Co	6.43 .12	6.76 .14	7.15 .10	6.50 .05	6.75 .09	6
Ni	5.75 .07	5.88 .05	5.86 .05	5.97 .04	6.02 .04	20
Cu			7.78	7.81	7.96	1
Zn				7.29	7.28:	1
Y	8.97:		9.44	9.10	9.32:	2
Y^+	9.42:	9.68 .23	9.99 .08	10.18 .09	10.30 .09	4
Zr	8.60 .16	8.64 .08		8.67		3
Ba^+	9.20	9.95 .14	9.50	9.44	9.30 .18	2
La^+	10.15:	10.58	10.68 .06	10.75 .12	10.91	3
Ce^+			10.82	11.44	11.31 .15	3
Pr^+			11.82	11.68		1
Nd^+	10.15	10.52	11.02 .09		11.15 .05	7
Eu^+		11.82	11.97	12.37:	12.43:	1

Table 4. The average abundances for V351 Cep in comparison with α Per and solar abundances

	$\log \varepsilon(X)$			$[X/Fe]_{V351Cep} - [X/Fe]_{Sun}$
	V351 Cep	α *Per*	*Sun*[1]	
C	−3.62	−3.70	−3.45	−0.07
N	−3.97	−3.46	−4.03	0.16
O	−3.09	−3.55	−3.13	0.14
Na	−5.39	−5.52	−5.67	0.38
Mg	−4.44	−4.28	−4.42	0.08
Al	−5.45	−5.43	−5.53	0.18
Si	−4.42	−4.34	−4.45	0.13
Ca	−5.58	−5.57	−5.64	0.16
Sc^+	−9.00	−9.27	−8.83	−0.07
Ti	−7.17	−6.62	−6.98	−0.09
V	−7.70	−7.55	−8.00	0.40
V^+	−8.32	−8.36		−0.22
Cr	−6.43	−6.18	−6.33	−0.00
Cr^+	−6.46	−6.33		−0.03
Mn	−6.66	−6.75	−6.61	0.05
Fe	−4.60	−4.59	−4.50	0.00
Fe^+	−4.62	−4.56		−0.02
Co	−6.67	−6.96	−7.08	0.51
Ni	−5.92	−5.84	−5.75	−0.07
Cu	−7.88	−7.35	−7.79	0.01
Zn	−7.29		−7.40	0.21
Y	−9.24	−8.88	−9.76	0.62
Y^+	−10.02	−9.70		−0.16
Zr	−8.63	−8.65	−9.40	0.87
Ba^+	−9.46	−9.94	−9.87	0.51
La^+	−10.69	−10.88	−10.78	0.19
Ce^+	−11.27	−11.32	−10.45	−0.72
Pr^+	−11.27		−11.29	0.12
Nd^+	−11.06	−11.10	−10.50	−0.46
Eu^+	−12.06	−11.48	−11.49	−0.47

[1] – Grevesse, 1993.

the young massive supergiant α Per significant nitrogen overabundance and carbon deficiency relative to the solar abundances were revealed, which was to be expected for the evolution stage of α Per. These results for CNO elements of V351 Cep suggest the absence of dredge-up of the H-burning products to its surface.

The neutral oxygen abundance derived from the equivalent widths of the strong lines of the OI infrared triplet λ 7771–7775 is larger by 0.4 dex than the value obtained from the permitted OI lines λ 6155–6158 Å. It is due to non-LTE effects for the infrared OI triplet lines (Faraggiana *et al.*, 1988) Therefore the infrared OI triplet lines have not been used for determinations of mean abundance values in Tables 3 and 4.

The overabundance of sodium, [Na/Fe] = +0.39 dex, is typical and well known for high luminosity stars. This phenomenon, repeatedly discussed during the last years, allows to conclude on dredge-up of the products of the Ne–Na cycle to the surface of stars. There is yet no general agreement on the nature of this excess, but we tend to consider the observed Na excess a consequence of non-LTE effects in atmosphere of supergiants (Klochkova, 1991b), and in the atmosphere of V351 Cep in particular. There are several arguments confirming such an opinion. First, as it follows from Drake (1990), the non-LTE equivalent widths for the subordinate NaI lines are essentially larger than the equivalent widths calculated in the LTE approach. We used just these lines in abundance calculations. Second, if the observed Na excesses in the atmospheres of massive supergiants are real, then we can assume that for planetary nebulae (PN) similar overabundances must be observed. But no Na overabundance is derived from PN spectroscopy (Clegg, 1989). Third, the overabundance of Na was also revealed for low mass supergiants RU Cen, U Mon (Luck and Bond, 1989), although in the case of a low mass star the conditions for Na nucleosynthesis during the H-burning process are not favorable. Therefore we are convinced that the obtained Na excess is an artifact, and this conclusion is in agreement with the absence of CNO variations.

The V and Co overabundances are explained by ignoring fine structure of atomic levels for these odd atoms. They are also revealed for α Per.

The deviation of abundances of heavy metals (from Y to Eu) from solar ones may also be explained by imperfections of the analysis method, as the same deviations were also derived for α Per that must not have variations of abundances of *s*- and *r*-process elements due to its evolutionary stage. We emphasize once again the necessity to perform a differential analysis of the studied star relative to a standard supergiant with similar parameters

The presence of 6707 Å Li doublet was suspected for some V351 Cep spectra, but additional observations are needed for more definite conclusions.

7 LUMINOSITY

The luminosity value $M_V = -0.8^{\mathrm{m}}$ was obtained for V351 Cep using the P-L relation for Population II Cepheids (Demers and Harris, 1974). However, the applicability of such a relation to V351 Cep is doubtful because, as noted above, V351 Cep has the solar chemical composition. Therefore we used another possibility for the luminosity estimation.

It is known that the infrared OI triplet intensity is a suitable parameter estimate luminosity of F, G stars (Ferro *et al.*, 1991). The total equivalent width of the infrared OI triplet lines for V351 Cep is equal to $\Sigma W_\lambda(\mathrm{OI}) = 0.69$ Å, which corresponds to the value $M_V = -3.0^{\mathrm{m}}$ from the calibration of Ferro *et al.* (1991). The obtained value of M_V is in good agreement with the result derived by Ferro (1984). We emphasize that the conformity of our equivalent widths of the OI triplet lines to the system of Ferro *et al.* (1991) was verified by the α Per spectrum (our estimate for α Per is $\Sigma W_\lambda(\mathrm{OI}) = 1.10$ Å).

8 RADIAL VELOCITY

The radial velocity measurement has been performed by a method which imitates the oscilloscopic comparator in a personal computer. The essence of the method is in comparison of the direct and mirrored line profiles, the effective wavelength corresponding to the location with a maximum range correlation between these profiles. The solar wavelength list (Pierce and Breckinridge, 1974) and the atlas of telluric absorption spectrum for the lower atmosphere (Curcio *et al.*, 1964) were used in the procedure of Vr measurements.

Detailed radial velocity measurements were performed for a single spectrum, aiming only at revealing a possible dependence of the radial velocity on the low level excitation potential for searching the expected radial velocity variation with depth in the atmosphere. More than 270 lines were measured throughout the whole spectral range and then 210 best lines were selected. The dependence of V_r on the excitation potential was not discovered within the error limit (better than 2 km s^{-1}). That allows to conclude on the absence of kinematic stratification of the atmosphere of V351 Cep. Note that this result restricts the absolute magnitude ($M_V > -5^{\rm m}$).

The data on phase variation of the radial velocity and the results of spectrophotometric measurements will be published elsewhere. The preliminary value of the radial velocity variability with the phase of the light curve is $\Delta Vr > 15$ km s^{-1}.

9 CONCLUSIONS

One can see from Table 4 that the abundances of all the elements (with the exception of CNO) for V351 Cep are similar to those for the young massive supergiant α Per. Thus, V351 Cep is not a typical population II Cepheid according to its metallicity and its chemical abundance curve. The most interesting result is the absence of considerable CNO abundance modifications.

The spectra of several objects related to V351 Cep have been studied earlier. Wallerstein (1979) derived the chemical composition of the Population II Cepheid V553 Cen, and neither essential carbon deficiency nor other evolutionary variations of chemical composition were revealed. Harris *et al.* (1984) studied the chemical composition of the peculiar Population II Cepheid AU Peg, obtained [Fe/H] = ± 0.1 dex and found that the abundances of 17 chemical elements did not differ from solar ones. Unfortunately, these papers have insufficient information about CNO abundances. Luck and Bond (1989) investigated the spectra of the brightest Population II Cepheid κ Pav and obtained the results coincident with ours for V351 Cep.

An important result of our study of V351 Cep is the discrepancy between the absolute magnitude derived from the P–L relation for halo Cepheids and that determined from the infrared OI triplet intensity. This fact, together with solar chemical composition, makes doubtful the ranking of V351 Cep among W Vir stars. On the other hand, combining parameters derived in this paper and those known earlier, we cannot classify V351 Cep as an ordinary Population I Cepheid in galactic disk either, because the shape of its light curve does not correspond to that for Population I Cepheids. A possible explanation of the observed properties of V351 Cep is a hypothesis that V351 Cep belongs to "anomalous cepheids" which may originate as a result of coalescence of two ordinary stars in a binary system (Wallerstein and Cox, 1984). Another possible explanation is binary nature of V351 Cep similar to the W Vir stars AU Peg (Harris *et al.*, 1984) and TX Del (Harris and Welch, 1989). We plan to continue spectral observations and measurements of radial velocities for testing this hypothesis.

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