Abundances of 4 Lacertae and ν Cephei

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Ankara University, Faculty of Science, Dept. of Astronomy and Space Sciences, 06100 Tandogan, Ankara, TURKEY
kyuce@astro1.science.ankara.edu.tr

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ABSTRACT

I have performed using Kurucz LTE model atmospheres detailed fine analyses of the supergiants 4 Lac and ν Cep. The spectral data were obtained at 1.22-m telescope of the Dominion Astrophysical Observatory (DAO) by Saul J. Adelman. The atmospheric parameters were derived using the wings of Hβ and Hγ profiles for each one star, and from Fe I/II, Fe II/III, Si II/III equilibrium for 4 Lac, and from Fe I/II, Cr I/II equilibrium for ν Cep. A microturbulence of 2.7 km s^{-1} for 4 Lac was found from Fe II lines while a mean value of 5.2 km s^{-1} for ν Cep from Cr II, Ti II and Fe II lines. The rotational and macroturbulent velocities are, respectively, 14 ± 2 km s^{-1} and 15 ± 2 km s^{-1} for 4 Lac, and 26 ± 2 km s^{-1} and 12 ± 2 km s^{-1} for ν Cep. Their He, CNO and light element abundances are solar or overabundant while iron peak and heavy element abundances are solar or underabundant. The derived results show that 4 Lac has nuclearly processed matter in its photosphere while ν Cep does not.

1. INTRODUCTION

4 Lacertae (HD 212593, HR 8541, BD +48°3715, SAO 51970, HIP 110609) and ν Cephei (HD 207260, HR 8334, BD +60°2288, SAO 19624, HIP 107418; 10 Cep) were classified as B9 Iab and A2 Ia, respectively, by Morgan & Roman (1950), Slettebak (1954) and Stock (1956). ν Cephei is a member of Cep OB2 association (Humphreys 1978). Hill et al. (1986) indicate that 4 Lac is a member of Lac OB1, but this is uncertain because of its large residual for the Mv-W(Hγ) calibration (see also Humphreys 1978).

For 4 Lac and ν Cephei which are for the most part unstudied supergiants in literature, their optical spectrophotometry remains to be obtained. Verdugo et al. (1999) derived as atmospheric parameters of 4 Lac (T_{eff} = 10000 K, log g = 1.5) from Balmer fits using LTE line blanketed plane parallel static model atmospheres. The effective temperature values are 10300 K (Schmidt-Kaler 1982) and 9932 K (Underhill 1982) for 4 Lac, and 9080 K (Schmidt-Kaler 1982) and 9120 K (Garmany & Stencel 1992) for ν Cep.

2. SPECTRA

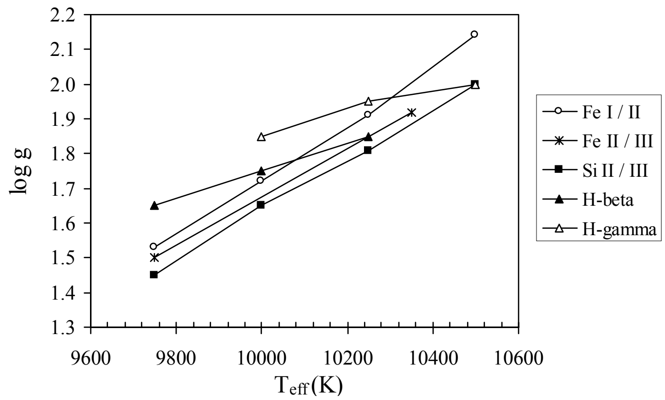
Saul J. Adelman obtained 2.4 Å mm^{-1} DAO CCD spectrograms which cover almost 63 Å for the SITe 2 and 147 Å for the SITe 4. Spectra between 3830 and 4950 Å have S/N > 250. The combination of these electronic devices with a high resolution spectrograph enables one to analyze profiles of even faint lines with high accuracy. I used the computer graphics program REDUCE and VLINE (Hill & Fisher 1986) to normalize and measure the spectra.

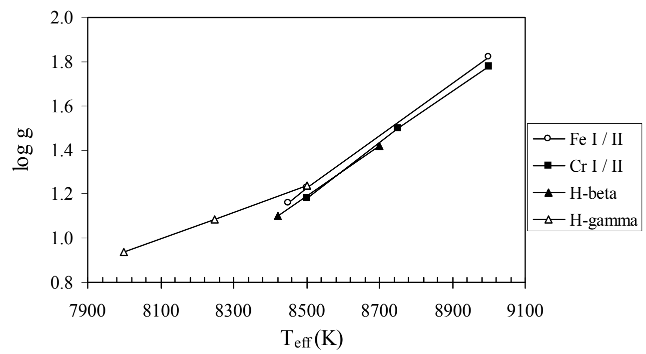
The scattered light in the direction of the dispersion was corrected as part of the extraction program CCDSPEC (Gulliver & Hill 2002).

My average radial velocity was –21.9 ± 5.1 km s^{-1} with an amplitude of 13.3 km s^{-1} for 4 Lac, and –20.1±5.0 km s^{-1} with an amplitude of 14.8 km s^{-1} for ν Cep. Values from literature are between –28 and –20 km s^{-1} for 4 Lac whereas they are between –25 and –15 km s^{-1} for ν Cep.

3. DETERMINATIONS

3.1. Atmospheric parameters: The effective temperature and surface gravity were derived using the Kiel diagram for each star. They contain pairs from ionization equilibria and the observed Balmer line wing fits with the calculated SYNTHE (Kurucz & Avrett 1981) profiles (Figures 1 and 2). The best atmospheric parameter pairs: T_{eff} = 10350 K and log g = 1.92 in 4 Lac, T_{eff} = 8500 K and log g = 1.25 in ν Cep.





Figures 1 and 2. Kiel diagrams for 4 Lac (left) and ν Cep (right).

Lemke (1989) finds that for main sequence stars the mean accuracy of atmospheric parameters are ±200 K in effective temperature and probably not larger than ±0.2 dex in surface gravity. These values are in accord with uncertainties of seven A0-A2 type supergiants derived from Hγ fits, Mg I/II ionization equilibrium by Venn (1995a). For the Kiel diagram of ν Cep, three of criteria have lines parallel to one another and thus it is difficult to get good range estimates. An examination of the Kiel diagram of 4 Lac by considering the intersections of the criteria indicates a maximum range of 400 K in effective temperature and 0.2 dex in surface gravity. Thus, the uncertainities found by Lemke appear also to be appropriate for 4 Lac and ν Cep.

3.2. Microturbulence and He/H ratio: The microturbulent velocity was determined from Fe II lines in 4 Lac, and from Cr II, Ti II, Fe II in ν Cep. We prefer using species having at least 20 lines with equivalent widths 5 mÅ or more including 5 with equivalent widths between 90 and 150 mÅ. In addition, the lines were selected as they are unblended and have reliable gf-values. Their abundances were calculated with WIDTH9 assuming various microtubulent velocities for a range of possible values. The adopted values for each species resulted in no dependence of the derived abundances on the equivalent width. Thus, the results tell us that 4 Lac has the microturbulent velocity of 2.7 km s^{-1} whereas ν Cep has the mean value of 5.2 km s^{-1}.

The He/H ratio were derived comparing the observed He I line profiles with synthesized spectra using the program SYNSPEC (Hubeny et al. 1994). The mean of derived He/H values from nine lines of 4 Lac is 0.154 ± 0.019 whereas it is 0.136 ± 0.004 for ν Cep.

3.3. Other Element Abundances: Using the derived microturbulent velocities ξ=2 km s^{-1} for 4 Lac and 4 km s^{-1} for ν Cep, selected atomic parameters, and ATLAS9 model atmospheres log (N/N_T) values were found for each line with a well determined equivalent width using WIDTH9. All abundance results, their comparisons with the Sun and similar type supergiants are presented in Yüce (2004). Furthermore it contains an estimation in the sensitivity of the abundances on the atmospheric parameter errors using models whose effective temperature is 200 K hotter and log g 0.2 dex greater than the adopted values.

The mean abundances show that 4 Lac is a slightly metal richer supergiant than ν Cep in light elements. On the other hand, 4 Lac is more metal poor than ν Cep for iron peak elements. Most of ν Cep's abundances are close to solar with a few exceptions: Ca, Sc, Ti, and Y while the earlier type 4 Lac is more variable in N, Si, Ar, Ca, Ti, Cr, and Sr. Nevertheless, both these early type supergiants tend to show the same abundance patterns relative to the solar, namely both stars seem to show that He, CNO and light element (Mg, Al, Si, S, Ar, Ca) abundances have solar values or are overabundant while the iron group elements (Sc, Ti, V, Cr, Mn, Fe, Ni) and the heavy elements (Sr, Y, Zr) abundances are generally solar or underabundant. Si and Ca, which are prototypical α- elements synthesized during hydrostatic burning of massive stars (Woosley & Weaver 1995), are overabundant. Sr and Zr from s- process elements are mildly underabundant in 4 Lac and ν Cep, respectively.

3.4 Macroturbulent and Rotational Velocities: In this study, the first estimates of the rotational velocities for 4 Lac and ν Cep were determined from measuring unblended symmetric lines (for examples; Fe II, Ti II) using VLINE (Hill & Fisher 1986). They are 16 km s^{-1} and 21 km s^{-1} , respectively.

To determine the rotational ($v \sin i$) and the macroturbulent (ζ) velocities for 4 Lac and ν Cep, the program SYNTHE (Kurucz & Avrett 1981) was used to calculate a synthetic spectrum for λλ4480-4559, a region with clean strong lines for each star. The synthetic spectra were compared to the normalized observations. Then the values of macroturbulent and rotational velocities were changed until the best fit was reached. For 4 Lac, the best values are $v \sin i$ = 14 ± 2 km s^{-1} and ζ = 15 ± 2 km s^{-1} while the optimum values for ν Cep are $v \sin i$ = 26 ± 2 km s^{-1} and ζ = 12 ± 2 km s^{-1}.

3.5. Evolutionary Status of 4 Lac and ν Cep: 4 Lac and ν Cep with M > 10 $M_\odot$ has also been investigated on their evolutionary patterns.

- The chemical abundances of these two supergiants help to illuminate the evolution of massive stars. The CNO surface abundances of a supergiant are the Zero Age Main Sequence (ZAMS) surface values that have possibly been modified by mixing (dredge-up) between the interior and outer envelope of a star. Since CNO elements only act as catalysts during hydrogen burning for a massive main sequence star, that the reduction of the abundances of C and slightly O and the increase of the abundance of N with the sum of the nuclei remaining constant is predicted. For 4 Lac, the surface abundances (C solar, N overabundant, and O slight underabundant) are evidence for CNO core-processed material being present in the photosphere. The atmospheric abundances of ν Cep (near solar C and N and a slight underabundance of O) are in agreement with the model in which the star initiated helium core ignition without visiting the red giant branch (RGB). The evolutionary path of ν Cep coincides with the non-rotating model given for the tracks of a 20 $M_{\odot}$ star by Maeder & Meynet (2001).

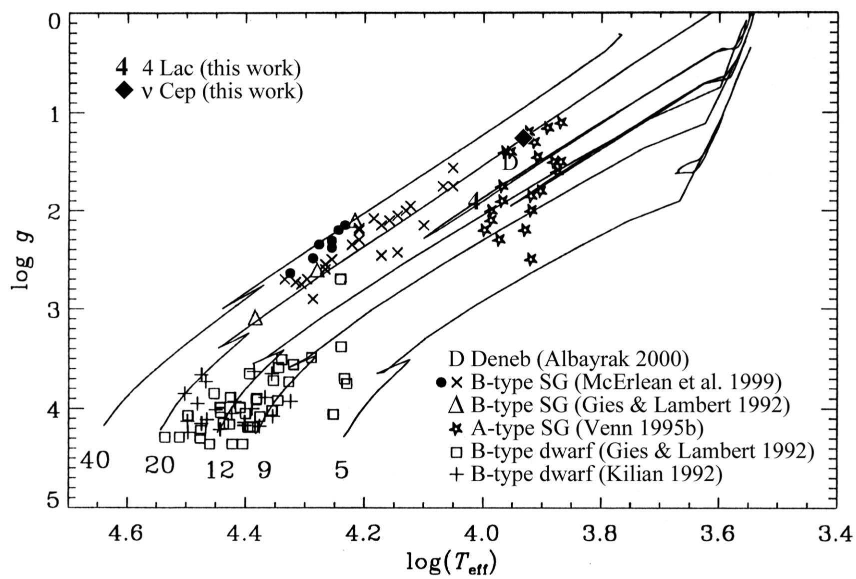
- I also compared the atmosphere parameters the supergiants with the theoretical calculations. Figure 3 shows the locations of our two supergiants, along with the solar metallicity evolutionary tracks of Schaller et al. (1992). It also contains similar type stars. This study's results put 4 Lac on the 12 $M_{\odot}$ track in the region near Venn's supergiants. This is agreement with the mass values of 4 Lac in literature (10-11 $M_{\odot}$). According to the figure, a main sequence early B star was the progenitor of 4 Lac. The atmospheric parameters of ν Cep place it on the 20 $M_{\odot}$ path which is a little above the track given by Lamers et al. (1995, 16 $M_{\odot}$). Thus ν Cep is more luminous than many of Venn's stars and in agreement with the moderate/normal processed B-type supergiants. ν Cep's main sequence progenitor would be of O-type.

- Thus when I examined the positions of two supergiants on the (log L – log T_{eff}) theoretical evolutionary paths of Schaller et al. (1992);

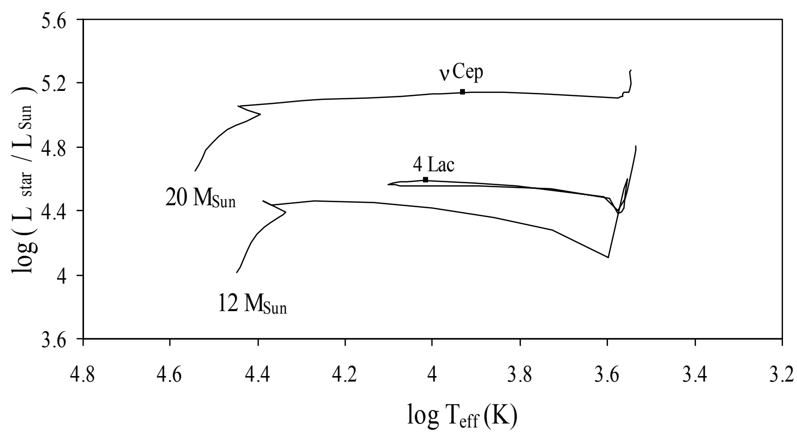
i) The values of R = 60 $R_{\odot}$ (Leitherer 1988) and T_{eff} = 10350 K (this study) of 4 Lac put it on the 12 $M_{\odot}$ evolutionary path (Figure 4). The star has evolved back from the red supergiants phase (on a blue loop). This position is the same as that in Figure 3 from its atmospheric parameters. Schaller et al. give the age of this point as 16 million years. It seems to be confirmed with the non-rotating model of 12 $M_{\odot}$ by Meynet & Maeder (2003). This age is in agreement with that of LAC OB1 association (16-25 x10^6 year, Blaauw 1958). This increases the probability that 4 Lac is a member of LAC OB1.

ii) ν Cep is on the 20 $M_{\odot}$ evolution calculation (Figure 4). Theoretical calculations provide an age of 8 x 10^6 year for that point, which was confirmed by Meynet & Maeder (2003). This age agrees with CEP OB2 (7-3 x 10^6 year in a and b sub-associations, Simonson and Someren Greve 1976).

iii) Both 4 Lac and ν Cep are more metal poor compared with the Sun. This study shows 4 Lac is slightly more metal poor than ν Cep, and 4 Lac has a bluer loop in HRD.



Figures 3. Positions of 4 Lac, ν Cep and some stars in T_{eff}-log g plane.



Figures 4. Positions of 4 Lac, ν Cep and some stars on the theoretical evolutionary paths of Schaller et al. (1992).

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