High Resolution Spectroscopy of the high galactic latitude RV Tauri star CE Virginis

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ABSTRACT

Analysis of the surface composition of the suspected cool RV Tauri star CE Vir shows no systematic trend in depletions of elements with respect to condensation temperature. However, there is a significant depletion of the elements with respect to the first ionization potential of the element. The derived Li abundance of log $\epsilon$ (Li) = 1.5±0.2 indicates production of Li in the star. Near infrared colours indicate sporadic dust formation close to the photosphere.

Key words: star: abundances — star: individual (CE Vir, RV Tauri, SRd variables) — star: FIP effect

1 INTRODUCTION

RV Tauri stars are low mass late type supergiant pulsators that show deep and shallow minima with periods ranging from 40 to 150 days. Their spectral types range from F5 to K3 although most of them are earlier than G3 (Lloyd Evans 1999). Preston et al. (1963) classified RV Tauris into three spectroscopic classes RVA, RVB and RVC. The RVAs are normal oxygen rich group, and RVBs show lines and bands of CI, CH and CN where as RVCs show weak metal lines and high radial velocities, and are thought to be metal poor. The RVA and RVB may belong to disk population. RVB and RVC stars are generally of earlier spectral type than RVA. The evolutionary status of RV Tauri stars is thought to be post-AGB (Jura 1986, Alcolea & Bujarrabal 1991) or at the end of AGB phase (Gingold 1986). Photospheric chemical composition is expected to give clues to their evolutionary status. Recent abundance analyses of a sample of field RV Tauri stars (Giridhar, Rao & Lambert 1994; Gonzalez, Lambert & Giridhar 1997a, 1997b; Giridhar, Lambert & Gonzalez 1998, 2000) revealed that stars with intrinsic metallicity $[\text{Fe}/H] < -1$ are not subjected to this composition anomalies resulting from dust-gas (DG) separation and subsequent accretion of the winnowed gas (Giridhar, Lambert & Gonzalez 2000). It is not presently clear where the site of dust formation and the dust-gas separation is taking place, whether in a circumbinary disk (Van Winkle et al 1999) or in the stellar wind (or circumstellar region) although many of the RV Tauri stars that exhibit the abundance anomalies are binaries.

In reviewing the process of dust gas separation Giridhar, Lambert & Gonzalez (2000) suggest that the absence of the anomalies in RVA stars is due to either inefficient return of gas to the atmosphere and/or to the dilution of this gas by the deeper convective envelope of the cooler stars. Since RVAs are likely to turn into RVBs the initiation of the return of the winnowed gas to the photosphere would be expected to happen in the RVA phase particularly in the coolest stars. Exploration of the coolest RVAs might give some clues to how the process gets initiated. CE Virginis is one of the coolest stars in which Giridhar et al (2000) find traces of abundance anomalies related to winnowed gas -their DG index of 1. We undertook to explore this star spectroscopically in more detail. CE Vir is thought to be a SRd star but Gonzalez et al. (1997b: hereafter GLG) consider it as a cool member of RV Tauri class based on the similarity with the bonified RV Tauri star DY Aql. CE Vir is also one of the two stars in a sample of 21 RV Tau stars with a strong Li I 6707 Å line and also located at high galactic latitude (57.8 degrees). Normally RV Tau stars at high galactic latitudes are expected to be RVC stars with weak metal lines but Gonzalez et al. (1997b) classify CE Vir as a RVA star.
Moreover the analysis of Gonzalez et al. is confined to a few elements only. Because of these interesting characteristics we obtained high resolution spectra of CE Virginis.

2 OBSERVATIONS

High-resolution optical spectra have been obtained with the Fiber-fed coude echelle spectrometer (Rao et al. 2004) of the 2.3 meter Vainu Bappu Telescope (VBT) on a few occasions. The spectra discussed and displayed here (Figures 1 to 4) have been obtained with VBT on 17 and 18 February, 2004. The spectrometer operates in a littrow mode and consists of a six element collimator-camera system that operates both as a collimator to the input beam and as a camera to the dispersed output beam. The collimated beam passes through a cross disperser prism twice; once before it reaches the echelle grating and once after the echelle grating. The main dispersing element in the spectrometer is a 408 mm × 204 mm echelle grating of 52.6 gr/mm with a blaze angle of 70 degrees. The input beam size is 150 mm. The dispersed spectrum is recorded on either a 2 K × 4 K, 15 micron pixel CCD or a 1 K X 1 K 24 micron pixel CCD camera. The star light is fed to the spectrometer from the prime focus of the telescope by an optical fiber of 45 meter length.

The present observations used 1 K × 1 K CCD system and covered the spectral region of 4980 to 8050 Å with gaps. The spectral resolving power achieved in these observation $R = \lambda/\Delta\lambda$ as estimated from $FWHM$ of weak terrestrial $O_2$ lines is 63,000. A signal to noise of 70 was obtained on an average for each of the spectra. Image reductions are performed using the IRAF software. Sample spectra are presented in Figure 1.

The spectra at these phases looked free of any molecular
Table 1. Radial Velocity Measurements of CE Vir

| JD   | km s⁻¹   |
|------|----------|
| MtStromlo | 2441380.2 -70.5 |
|        | 1464.1 -69.4 |
|        | 1466.0 -71.2 |
| Mcdonald | 2450182.72 -73.1 ±1.2 |
|        | 1286.65 -77.0 ±1.1 |
| VBT   | 2453053.45 -69.8 ±1.1 |

lines except weak CN lines at 8010 Å region (which we tried to use for estimating N abundance - discussed further in other sections). The only emission conspicuously present is Hα (Figure 1) which has a central deep absorption flanked by emission peaks on either side. Slight line asymmetries might be present to a few lines but no line doubling or splitting is evident at this resolution, thus the spectrum seemed to be amenable for abundance analysis. The spectrum appears similar to a 1996 July spectrum of CE Vir discussed by Gonzalez et al. (1997b). The period of the light variations are very uncertain even though General Catalogue of Variable Stars (GCVS) gives it as 67 days with uncertainty. Recent analysis of the Hipparcos epoch photometry by Percy & Kolin (2000) could not result in any one definitive period. Thus the relative phase of Gonzalez et al.’s (1997b) observations to ours cannot be ascertained.

The star has a Tₚₐ similar to Arcturus; as such we have used the Atlas of the Arcturus spectrum (Hinkle et al 2000) for line identification along with the spectrum of K2 III star DZAnd (Goswami, Rao & Lambert 1998).

3 RADIAL VELOCITY

CE Virginis seems to be mildly variable in radial velocity. Although no systematic measurements are available, the star seem to have been observed on three occasion’s. Jones and Fisher (1984) obtained 3 measurements with a mean of −70.4±0.7 km s⁻¹ at Mt.Stronom; too not different from the recent measurements. Table 1 lists the individual measurements (both McDonald and VBT measured by us).

Based on the light curve it is not clear whether CE Vir is a SRd variable or an RV Tauri variable, although GCVS classified it as a RV Tau of 67: day period with light amplitude of 2.3 magnitudes in visual. Earlier Harvard classifiers called it SRd (Hoffleit 2000). Lloyd Evans (1999) has studied the total visual light amplitude of RV Tauri stars with respect to spectral type across the instability strip. For stars of CE Vir spectral type (K2), the light amplitude expected is about 0.3 not 2.3 magnitudes. The radial velocity variations (shown in Table 1) do not suggest a large pulsation amplitude. However the B-V colour of 1.39 noted at maximum light by Dawson & Patterson (1982) is consistent with the colour expected of a K2 Supergiant (1.36).

Dawson (1979) lists CE Vir as SRd with a period of 85 days. There seems to be some dichotomy about the period and luminosity if CE Vir is assumed to be a RV Tau star obeying the period luminosity relation (Pollard & Lloyd Evans 1999). The Tₚₐ and log g obtained (see below) places the star on a log L/Lₜ ≈ 3.5 track for post-AGB stars passing through the RV Tauri instability strip in the log g - Tₚₐ plane (Giridhar et al. 2000). This value of luminosity suggests a period of 330 days. On the other hand if a period of 67 days is assumed the Mᵥ expected is about 1.33 and is inconsistent with the luminosity estimated from Tₚₐ and log g.

4 DESCRIPTION OF THE SPECTRUM

Apart from the general weakness of the line spectrum, the spectrum of CE Vir is similar to α Boo. The lines in CE Vir are slightly broader and thus blended than in α Boo. A few aspects are different. As was discovered by Gonzalez et al. (1997b) Li I I λ 6707 line is very strong in CE Vir. The Na I D lines are accompanied by 2 (or 3) sharp interstellar components (Figure 2) that are red displaced relative to stellar lines and are present at radial velocities of −11 km s⁻¹, 8 km s⁻¹ (and possibly at 32 km s⁻¹). The stronger component at −11 km s⁻¹ is also present in K1 λ 7665 resonance line.

In addition to the interstellar components, both Na I and KI resonance lines seem to have red displaced circumstellar components (Figure 2). The components are displaced by about 10 km s⁻¹ from the main stellar line. If the stellar and the red circumstellar components are assumed to be gaussians (mainly for K I lines) the deblended equivalent widths of the components can be estimated. We examined whether other resonance lines show such components. In our observes spectral range Fe I lines λ 5110 and λ 5060 show red absorption components at the same displaced velocity. Similar red displaced components are also observed in the suspected RV Tauri star QY Sge (Rao, Goswami, & Lambert 2003). This gas is either falling back after an expansion due to pulsation or some infall from a circumstellar reservoir. Since only Na I D, K I and Fe I resonance lines show these components, the gas must be very cool and neutral.

As already mentioned Hα shows a deep absorption corresponding to stellar velocity flanked by emission on each side symmetrically displaced to either side by 32.5 km s⁻¹. The profile is also similar on the two occasions observed in 1996 by Gonzalez et al. (1997b). Only the central absorption and emission peaks are slightly displaced by few km s⁻¹.

Table 2. Photometry of CE Vir

| JD/date  | V   | B-V | U-B | Ref.   |
|----------|-----|-----|-----|--------|
| 2442886.7 | 10.71 | 0.99 |     | Dawson (1979) |
| 2887.7   | 10.64 | 0.98 |     |        |
| 4691.74  | 8.66  | 1.39 | 1.19 | Dawson and Patterson (1982) |
| 4704.71  | 9.13  | 1.43 | 1.46 |        |
| J  H  K  | 6.259 | 5.615 | 5.407 | 2MASS |
|         | 5.964 |     |     | DENIS |

Note:- J, H, and K magnitudes have typical errors of 0.02 (2MASS) and 0.07 (DENIS) magnitudes.
Figure 2. Profiles of Na D1 (solid) & D2 (broken) and K I (\(\lambda 7665\) Å) are shown in Heliocentric radial velocity units. Interstellar components are marked as IS.

Table 3. Na I and K I IS components

| Comp.1 | Rad. vel \(\text{km s}^{-1}\) | Eq.W \(\text{mÅ}\) |
|--------|------------------|-----------------|
| Na I D2 | −11.3            | 92              |
| D1     | −11.35           | 64              |
| K II (\(\lambda 7665\)) | −11     | 17              |
| Comp.1 | Na I D2          | 8.2(*)&        |
| D1     | 7.3              | 12              |

* - contaminated by terrestrial H2O line.

5 ABUNDANCE ANALYSIS

Gonzalez et al.’s (1997b) analysis was confined to a few elements. In the present analysis, we tried to obtain estimates of the line strengths of as many elements as we can identify unambiguously. We follow the traditional LTE, Kurucz model atmospheres based analysis for a given metallicity parameter([M/H]), using the current version of MOOG (Snedan 1973). One of the critical choices to be made is the assumed model [M/H] value. It is obvious from Gonzalez et al.’s (1997b) analysis that the Si and Mg have different abundances (i.e [X/H]≃ −0.7 ) to Fe ( [Fe/H]≃ −1.3) -the main electron donors to continuous opacity. A change in [M/H] from −0.7 to −1.3 changes the abundance of ionised metals by 0.15 dex. We have assumed [M/H] of −1.0 (same choice as Gonzalez et al. 1997b). This leads to an uncertainty of
around 0.07 dex. The $gf$ values have been obtained from the following sources: Reddy et al 2003, Lambert et al 1996, and compilation by R. E. Luck (private communication). The excitation and ionisation equilibria are taken care by ensuring the same abundance for both high and low excitation lines of Fe I as well as Fe I and Fe II. The ionization equilibrium from Ti I/ Ti II and Cr I/Cr II are also kept satisfied. The final model arrived at is $T_{\text{eff}}$ of 4300 K, $\log g = 0.25$, the microturbulent velocity $\xi_t = 3.4$ km s$^{-1}$, and [M/H] of $-1.0$, some what similar to the parameters obtained by Gonzalez et al. (1997b). The resulting abundances are displayed in table 4. The Li abundance is arrived at by synthesizing the spectrum in $\lambda$ 6707 region (Figure 3) with critically examined line list (Reddy et al. 2002) in the vicinity of the Li I $\lambda 6707$. The resonance line of Li I $\lambda 6707$ is a blend of $^6\text{Li}$ and $^7\text{Li}$ isotopes and their multiple HFS components.

Wavelengths and log $gf$ values for all the components were adopted from Hobbs, Thorburn, & Rebull (1999). In computing Li abundance, isotopic ratio $^6\text{Li}/^7\text{Li} = 0.0$ has been assumed. With the above input atomic data and the derived model, we obtained Li abundance $\log \epsilon(\text{Li}) = 1.5\pm0.2$. The excited Li I line at $\lambda$ 6103 is very weak and we could only estimate an upper limit of 1.5 dex by way of spectrum synthesis (Figure 4), using the line list from Kurucz (1994). This is quite different from the value $-0.40$ to $-0.03$ given by Gonzalez et al. (1997b).

An upper limit to carbon abundance estimated by synthesizing the C I line $\lambda 5380$ (within the detection limit) is found to be $\leq 7.76$. A Nitrogen abundance of $\leq 7.0$ is estimated using the upper limit of C and synthesizing the red CN lines in the $\lambda$ 8030 region. The oxygen abundance

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**Figure 3.** Determination of total Li abundance from spectral synthesis of Li I line at 6707.6 Å. Synthetic spectra (lines) have been computed for three different Li abundances and compared with the observed Li profile (filled circles).
is obtained from the strong [O I] lines 6300 Å and 6363 Å. Clearly C/O < 1.

The K abundance is estimated from K I resonance lines making an allowance for the redward circumstellar component (an estimate is also made without making this allowance) thus might be uncertain.

### 6 ABUNDANCE TRENDS

It has been suggested by Gonzalez et al. (1997b) that the pattern of abundances in CE Vir are generally like that seen in warm RV Tau stars except that only the elements with highest $T_c$ are depleted. It is obvious from their figure that the abundances of Na and Mn are not consistent with that suggestion. Both are much more depleted than Si and Mg which have much higher $T_c$. In the entire sample of RV Tau stars analysed Na is either enhanced or of the same depletion value as Zn, S., never much less -thus CE Vir is unusual.

We compared our values of [X/H] with those obtained by Gonzalez et al. They show no major differences except for Li. The average difference for 13 elements (ours - GLG) is just $-0.007 \pm 0.11$. The depletion of Na and Mn are confirmed (different lines used than those by GLG).

In Figure 5, we plot the $T_c$ versus our [X/H] from Table 4. $T_c$ here is taken as the condensation temperature where 50% gas is condensed into solid form as estimated for solar system abundances and a pressure of $10^{-4}$ bar by Lodders (2003). It is obvious from the figure that no single systematic pattern emerges. This is totally untypical of warm RV Tau stars (eg. IW Car - Giridhar, Rao & Lambert 1994). It is apparent that the abundance pattern exhibited...
Figure 5. Abundance depletions \([X/H]\) are shown against condensation temperature.

by CE Vir is neither consistent with that generally expected from metal poor stars nor warm RV Tau stars.

On the other hand in Figure 6 the \([X/H]\) values obtained by GLG are plotted with respect to the first ionization potential (FIP) of the element. Figure shows a definite trend, although some scatter is present; the lower the ionization potential the higher is the depletion. Our more extensive data from Table 4 are plotted in the Figure 7. Clearly it is obvious from the Figure 7, that for element whose first ionization potential is below 8 eV depletion occurs, lower the ionization potential higher is the depletion. Even Na shares this pattern. Sc does seem to be slightly more depleted than the trend for other elements.

Giridhar, Lambert & Gonzalez (1998, paper IV) did examine the possibility of depletions being correlated with first ionization potential of the element in other warmer RV Tau stars eg. AD Aql. They however discounted this possibility on the grounds that the alkalis Na and K and Al do not fit into the ionization potential versus \([X/H]\) trend of other elements. Secondly the trend with \(T_c\) has less scatter. The situation in CE Vir is quite different. All three so called discordent elements do fit into general trend. K abundance is estimated from two resonance lines, which have red displaced circumstellar components. (the abundance or deficiency estimate is not affected much by either including or excluding the circumstellar component). Even Li fits this pattern quite well (coincidence?). If real, this implies that the undepleted abundance of Li is about solar system value of 3.31 which suggests Li has been re-manufactured during its evolution.
7 DISCUSSION

Abundance correlations with ionization potential in Pop II variables has been in vogue for a long time eg. W Vir (see the foot note in Barker et al. 1971). In CE Vir this clearly seems to be present for elements with first ionization potentials below $\simeq 8 \text{eV}$. It is likely that singly ionized elements escaped as stellar wind probably controlled by magnetic fields (open field lines ?) rather than coupled to radiation pressure on dust (presence of dust in the atmosphere is not convincing in this and other similar stars e.g.,DY Aql).

What provides the extra source of ionization to the atmospheric gas is not clear. The velocity variations, the amplitude of light curve and the period of pulsation are very uncertain presently for CE Vir. The pulsation amplitude is likely to be small (based on the radial velocity measurements obtained so far). Whether atmospheric shocks can provide this ionization is not clear. It is true that the star shows H$\alpha$ emission like a Be star - a disk or shell of emitting gas is present. The photon energies needed to ionize H would be too high for the trend seen here.

Is there still some evidence for dust-gas separation ($T_c$ versus abundance depletion?) Sc abundance does suggest in a mild way such a possibility considering the extra depletion suffered. Does circumstellar dust exist in the environment of CE Vir? Recently (since the paper by GLG 2000) the 2MASS (Cutri et al. 2003) and DENIS near IR photometry became available and is shown in Table 2.

The two sets of measurements do show variability of the near IR flux. The J magnitude changed by 0.3, more importantly the K magnitude changed by 0.8. The near IR colours of RV Tau stars have been discussed by Goldsmith et al. (1987). 2MASS colours of CE Vir are marginally outside the region seen for G to M giants in J-H versus H-K.
diagram (other cool RV Tau star, DY Aql lies within this region). But DENIS colours are appreciably different and suggests excess radiation particularly at K band, indicative of the presence of hot dust. The variability of K magnitude probably suggests sporadic formation of dust. In summary there is evidence for presence of hot ($\approx 1200 \text{--} 1300$ K) dust.

The picture that emerges is that stellar wind, probably controlled by magnetic fields, (see Pascoli 1997; Garcia-Segura et al. 2004 for magnetic field driven winds in post-AGB stars) puts the gas into circumstellar regions in which sporadic dust formation occurs. There is also evidence from resonance lines of Fe I, K I and Na I that some of the cool gas (co-inhabited with dust?) returns to the star.

CE Vir, being the coolest member of the group, might show the initiation of the dust-gas separation activity. It is unlikely that cool stars like DY Aql, CE Vir have enormous amounts of dust manufactured in their atmospheres which would then drag the gas away by radiation pressure. If dust is manufactured in some cool circumstellar region (disk, shell), radiation pressure on dust can not be the source to put the photospheric gas into the shell. The other likely mechanism is the pulsation. It is not clear atleast in CE Vir, the pulsation would be strong enough to eject gas (and start stellar wind). If it is not strong enough, the other mechanism could be the magnetic field driven wind pulling the ionized gas with it. CE Vir suggests such a possibility. Would such evolved stars still retain surface magnetic fields is a question to be explored. What provides the extra ionization in CE Vir is still a mystery.

Very recently Giridhar et al. (2004) further estimated surface abundances for a sample of dozen new RV Tauri stars. One of the stars, EQ Cas, is unique and displays an abundance pattern that is quite different from other RV

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Abundance depletions [X/H] are shown against first ionization potential.}
\end{figure}
Tauri stars that were affected by dust - gas separation. However it shows a great similarity to the abundance pattern presented in this paper for CE Vir. Elements like Na, Mn etc. whose \(T_c\)s are much lower than that of Si, Mg etc. are much more depleted than Si and Mg, contrary to what is expected in dust condensation scenario. However the same depletion values ([X/H]) are well correlated with first ionization potentials for elements below 8 eV (Figure 8), as seen for CE Vir. Thus EQ Cas looks like a twin of CE Vir. EQ Cas also shows at certain phases \(T_{\text{eff}}\) of 4500 K, \(\log g = 0.0\), micro turbulent velocity \(\xi_t = 4.6 \text{ km s}^{-1}\), and \([\text{M/H}]\) of \(-0.8\) similar to CE Vir. It is also a high velocity star with a radial velocity of \(-158 \text{ km s}^{-1}\). 2 MASS data provides J, H, K magnitudes for EQ Cas. The J - H, and H - K colours do not suggest near IR flux excess.

The phenomenon shown by CE Vir and EQ Cas might not be uncommon (2 out of about 35 stars) among RV Tauri stars. Particularly cooler stars might be more prone. The abundance patterns displayed by both CE Vir and EQ Cas, namely a strong correlation of increasing elemental depletion with decreasing FIP, suggest operation of stellar wind that selectively removed the low FIP elements from the photospheres of the stars. A striking similarity can thus be seen in composition with slow solar wind. It is long been known that slow solar wind, which arises mainly from lower solar latitudes, and the solar corona both show a dependence of elemental abundances on the first ionization potential. The elements with FIP \(< 10 \text{ eV}\) (eg., Mg, Si, Fe etc.) show abundance enhancements by a factor of 4 relative to their photospheric values, whereas the elements with FIP \(> 10 \text{ eV}\) (eg. O, S, Ne etc.,) do not show such enhancements - the FIP effect (Geiss 1982; Geiss et al. 1995). Although there is no

Figure 8. Abundance depletions [X/H] against first ionization potential for EQ Cas. Abundance results are taken from Giridhar et al. (2004).
photospheres show the leftover gas after FIP effected winds, whereas spheres are unaffected. In case of CE Vir and EQ Cas, the effect in their coronae (and possibly winds) their photospheric and internal structure (Garcia-Alvarez et al. 2004). Solar-like FIP effect, despite their clear non-solar evolution, is believed to be present in stellar coronae of solar type (inactive) stars (e.g., mainly in the chromosphere. FIP effects are also thought to be in the upper chromosphere (Henoux 1998). Although Sun and other solar-type stars show the FIP effect in their corona (and possibly winds) their photospheres are unaffected. In case of CE Vir and EQ Cas the photospheres show the leftover gas after FIP effected wind has modified the atmosphere. It is possible either that the elemental fractionation could have occurred (or occurring) on the photospheres or fractionated gas has been accreted on to the photosphere from circumstellar regions that were swept by FIP effected wind. Thus, the realization of counter FIP effect (deficiency correlation with FIP) in CE Vir and EQ Cas acquires special significance. It would be of great interest to trace in CE Vir and EQ Cas the presence of either the stellar wind, its composition and/or chromosphere or corona that might show FIP effect.

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Table 4. Abundance Summary for the CE VIR. Solar abundances and the condensation temperatures ($T_C$) for the solar system composition are adopted from (Lodders 2003). The last column $\chi I$ is the first ionisation potential of the element X.

| Species | log $\epsilon$ ($X/\odot$) | n | log $\epsilon$ (X) | [X/H] | $T_C$ (K) | $\chi I$ (eV) |
|---------|-----------------|---|-----------------|-------|-----------|-----------|
| Li I | 3.28 | 1 | 1.50 | $-2.03$ | 1142 | 5.39 |
| O I | 8.69 | 2 | 8.23 | $-0.46$ | 180 | 13.62 |
| Na I | 6.30 | 3 | 4.92 | $-1.38$ | 958 | 5.14 |
| Mg I | 7.55 | 6 | 6.95 | $-0.60$ | 1336 | 7.65 |
| Al I | 6.46 | 3 | 4.79 | $-1.67$ | 1653 | 5.99 |
| Si I | 7.54 | 5 | 6.71 | $-0.83$ | 1310 | 8.15 |
| K I | 5.11 | 2 | 3.17 | $-1.94$ | 1006 | 4.34 |
| Ca I | 6.34 | 8 | 4.73 | $-1.61$ | 1517 | 6.11 |
| Sc I | 3.07 | 1 | 0.78 | $-2.29$ | 1659 | 6.56 |
| Sc II | 3.07 | 2 | 0.60 | $-2.47$ | ... | ... |
| Ti I | 4.92 | 12 | 3.78 | $-1.14$ | 1382 | 6.83 |
| Ti II | 4.92 | 5 | 4.01 | $-0.92$ | ... | ... |
| V I | 4.00 | 4 | 2.62 | $-1.38$ | 1249 | 6.75 |
| V II | 4.00 | 2 | 2.86 | $-1.14$ | ... | ... |
| Cr I | 5.65 | 3 | 5.39 | $-1.72$ | 1296 | 6.77 |
| Cr II | 5.65 | 3 | 4.39 | $-1.26$ | ... | ... |
| Mn I | 5.50 | 2 | 3.65 | $-1.85$ | 1158 | 7.43 |
| Fe I | 7.47 | 21 | 6.28 | $-1.19$ | 1334 | 7.90 |
| Fe II | 7.47 | 5 | 6.22 | $-1.25$ | ... | ... |
| Co I | 4.91 | 7 | 3.95 | $-0.96$ | 1352 | 7.88 |
| Ni I | 6.22 | 12 | 4.95 | $-1.27$ | 1353 | 7.73 |
| Cu I | 4.26 | 2 | 2.82 | $-1.44$ | 1037 | 7.73 |
| Zn I | 4.63 | 1 | 3.96 | $-0.67$ | 726 | 9.39 |
| Y I | 2.20 | 1 | 0.69 | $-1.51$ | 1659 | 6.22 |
| Zr I | 2.60 | 2 | 0.79 | $-1.81$ | 1741 | 6.63 |
| Zr II | 2.60 | 1 | 1.28 | $\geq -1.32$ | ... | ... |
| Mo I | 1.96 | 2 | 0.76 | $-1.20$ | 1590 | 7.09 |
| Ba II | 2.18 | 1 | 0.34 | $-1.84$ | 1455 | 5.21 |
| La II | 1.18 | 2 | $-0.57$ | $-1.75$ | 1578 | 5.58 |
| Nd II | 1.46 | 1 | $-0.11$ | $-1.57$ | 1602 | 5.53 |
| Eu II | 0.52 | 1 | $-0.60$ | $-1.11$ | 1356 | 5.67 |
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