

# The Determination of Abundances of Two RV Tauri Stars, U Mon and RV Tau

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## 2つのおうし座RV型変光星、 いっかくじゅう座U星とおうし座RV星の化学組成の決定

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### ABSTRACT

We observed two RV Tauri variables, U Mon and RV Tau, and we determined the chemical abundances of these stars in order to decide the right or wrong of the three proposed mechanisms which explain the anomalous chemical abundance of the RV Tauri variables.

The observations were made with the Echelle Spectrograph attached to the 150cm reflector at Gunma Astronomical Observatory in Gunma prefecture in Japan. Data reduction was carried out using standard techniques within the IRAF image processing software. The analysis was done by a sort of the differential curve-of-growth method, where the sun was selected as the comparison star, using the program made by Yoshioka.

The following results were obtained.

- 1) There is a slight correlation between the abundance relative to the sun and the condensation temperature for RV Tau that the  $[M/H]$  values decrease with the condensation temperature, though the scatters are large, which indicates that dust-gas separation mechanism may prevails in RV Tau. On the other hand, there is not the correlation for U Mon, which indicates that dust-gas separation mechanism does not prevails in U Mon.
- 2) The above correlation of the group A star, U Mon and RV Tau, confirms the results by Giridhar et al. (2000)<sup>12)</sup>, who observed that the group B show the pattern of abundance ascribed to the dust-gas separation mechanism, but the stars of the group A show the abundance which are very largely unaffected by the dust-gas separation mechanism.
- 3) According to our mean values of  $[Fe/H]$  for U Mon and RV Tau, the above results of 1) does not confirm the results by Giridhar et al. (2000)<sup>12)</sup>, who observed that the post-AGB stars with an intrinsic  $[Fe/H]$  lower than  $-1$  are not subject to the effects of the dust-gas separation.
- 4) There is not a correlation between the relative abundance and the first ionization potential of the element for both of the stars, which indicates that the first ionization mechanism does not prevails in both of the stars.
- 5) There is not a correlation between the relative abundance and the second ionization potential of the element for both of the stars, which indicates that the second ionization mechanism does not prevails in both of the stars.

It is desired that these stars should be reanalyzed by a different process of the differential curve-of-growth analysis, in order to confirm our results.

### 要 旨

われわれは、おうし座RV型変光星の化学組成の異常を説明する3つの説の当否を決めるため、2個のおうし座RV型変光星、U MonとRV Tauを観測し、これらの星の化学組成を求めた。

観測は、県立ぐんま天文台の150cm反射望遠鏡に取り付けたエッセル分光器を用いて行った。整約はソフトウェアIRAFを用いて行い、解析は吉岡が作成したプログラムを用いて、太陽を比較星とする一種の相対成長曲線法で行った。

そして、次の結果が得られた。

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- 1) RV Tauでは、太陽に相対的な元素量は、散らばりは大きい、凝縮温度と相関関係を示し、 $[M/H]$  の値は凝縮温度が高いほど小さい。この結果は、RV Tauでダスト・ガス凝縮が働いている可能性のあることを示している。一方、U Monでは相関関係が見られず、ダスト・ガス凝縮の起きていないことを示している。
- 2) Aグループの星であるU MonとRV Tauでの上述の相関関係は、Bグループの星にはダスト・ガス凝縮が見られるが、Aグループの星には明確には見られない、というGiridhar et al. (2000)<sup>12)</sup> の結果を確認するものである。
- 3) U MonとRV Tauの  $[Fe/H]$  の値によれば、2) の結果は、もとの  $[Fe/H]$  の値が $-1$ よりも小さなpost-AGB星はダスト・ガス凝縮の影響を受けない、というGiridhar et al. (2000)<sup>12)</sup> の結果は確認しない。
- 4) 両星とも相対的な元素量が各元素の第1電離ポテンシャルと相関関係が見られず、第1電離機構が働いていないことを示している。
- 5) 両星とも相対的な元素量が各元素の第2電離ポテンシャルと相関関係が見られず、第2電離機構が働いていないことを示している。

以上の結果を確認するために、成長曲線法の異なる方式で再解析することが望まれる。

## I. Introduction

The RV Tauri variables are pulsating ones whose light curves are characterized by alternative deep and shallow minima. The photospheres of many of these variables lack in heavy elements. On the basis of light curves the RV Tauri variables are divided into 2 subgroups, RVa and RVb. The RVa group is characterized by a relatively regular light curve, on the other hand, the RVb group is characterized by a superimposition of a long-term brightness variation upon the brightness variation with pulsation. On the basis of spectroscopic characteristics in an optical region the RV Tauri variables are divided into 3 groups, A, B, and C. The spectra of the group A show the characteristics of indicative of solar abundance, while the spectra of the group B show that of indicative of an enhanced carbon abundance. The group C shows many characteristics of the group B except that the carbon features are weak. Many of the stars of the group C belong to globular clusters.

The RV Tauri stars are considered to belong to Post-AGB stars. Many of the RV Tauri stars lack in metallic abundance and show peculiar chemical abundances. The peculiar abundances seem to be a result of the following factors; 1) the abundance of the interstellar matter from which the star were born; 2) the abundance of the matter which is experienced thermonuclear fusion in the interior of the star and is dredged up from the interior; 3) the abundance of the matter which is experienced the change in abundance by some mechanism. Especially, the third factor is considered to the main factor in the peculiar abundance.

The following mechanisms are considered as a candidate for the above main factor; a) The abundance derived from the lines of the neutral species is smaller than the true abundance, because the neutral species are overionized. The smaller the first ionization poten-

tial is, the larger the degree of overionization become. This mechanism is hereafter referred to as the first ionization mechanism; b) The photospheric gas is thermalized by a shock wave during brightening period and then the ionized hydrogens recombine free electrons and radiate a large quantity of Lyman-continuum photons. These photons overionize other elements. As a result, the singly-ionized species whose second ionization potentials are smaller than the first ionization potential of hydrogen, i.e., 13.60eV, are overionized, and abundance derived from the lines of singly ionized species is smaller than the true abundance. This mechanism is hereafter referred to as the second ionization mechanism; c) When the dusts are formed in the circumstellar envelopes, the refractory elements are preferentially taken in the dusts. Consequently, the circumstellar gas lack in the refractory elements. These gas accretes the photosphere of the star, and the photospheric gas becomes lacking in the refractory elements. This mechanism is hereafter referred to as the dust-gas separation mechanism.

In this study, we investigate the validity the above three mechanisms for the above main factor in the peculiar abundance. We have made spectroscopic analyses of U Mon and RV Tau, which belong to the RV Tauri variable.

## II. Observations

We have analyzed the spectra of U Mon and RV Tau. The spectra used in the present analysis were selected from the spectra taken with the Echelle Spectrograph attached to the 150cm reflector at the Gunma Astrophysical Observatory (hereafter referred to as GAOES). We selected the spectra taken near secondary light minima, because the spectral change due to pulsation is slow near light minimum and LTE seems to be a good approximation near secondary light minimum. If we add a few words, the spectra near primary light show emission lines, which indi-

cates that a shock wave passes the photosphere and LTE is not a good approximation. We selected the spectrum of U Mon which was taken on November 30, 2010 and the spectrum of RV Tau which was taken on December 7, 2008. The spectra of U Mon was taken at the phase between the primary light maximum and the secondary light minimum. The spectra of RV Tau was taken at the phase near the secondary light minimum. The spectral resolution was about 60000 and S/N ratio was about 100. The spectra cover the range from 450nm to 640nm. This spectral range was selected because there are many metallic lines in a short wavelength range and its range include neither H $\alpha$  line nor H $\gamma$  line which give a bad influence in the measurement of equivalent widths of metallic lines.

Data reduction was carried out using standard techniques within the IRAF image processing software. Calibration i.e. biases, flat fields, ThAr comparison lamps, were taken on every night. The reduction process included bias removal, scattered light subtraction, flat fielding, order extraction, and wavelength calibration.

The absorption lines used for reduction were selected on referring to the line list by Thevenin (1989)<sup>1)</sup> and Thevenin (1990)<sup>2)</sup>. The line list of the solar spectrum by Moore et al. (1966)<sup>3)</sup> was also referred for the selection of absorption lines.

The analysis was done by a sort of the differential curve-of-growth method in the following process. First, we obtained the values  $X$ ,  $Y$ , and  $\theta_{\text{ex}}$ , where  $X$  and  $Y$  are a difference in abscissa and in ordinate, respectively, between an observed curve-of-growth and a theoretical curve-of-growth, and  $\theta_{\text{ex}}$  is the reciprocal excitation temperature,  $5040/T_{\text{ex}}$  ( $T_{\text{ex}}$  is an excitation temperature). In the observed curve-of-growth, the  $\log_{10}W/\lambda$  values are plotted in the ordinate and the  $\log_{10}gf\lambda + \theta_{\text{ex}} \cdot \Delta\chi$  values are plotted in the abscissa, where  $\Delta\chi$  is the difference between the ionization potential and the lower excitation potential (for singly-ionized lines,  $\Delta\chi$  is negative and its absolute value is the ordinary lower excitation potential). On the other hand, the values of  $\log_{10}(Wc/2RcV_D\lambda)$  values are plotted in the theoretical curve-of-growth, where  $c$  and  $V_D$  are the speed of light and the Doppler velocity, respectively;  $Rc$  is the limiting central depth for strong lines. The following values are plotted for the abscissa of the theoretical curve-of-growth;  $\log_{10}gf\lambda + \log \langle N \rangle + \log C$ , where  $\langle N \rangle$  is the average value of the number density for the lower energy level of the relevant absorption line in the atmosphere and  $C$  is a constant.  $C$  is selected so as to the values of the abscissa agree with those of the ordinate for weak lines. The theoretical curve for pure absorption in the Milne-Eddington atmosphere calculated by Hunger

(1956)<sup>4)</sup> was used. The program made by Yoshioka (1987)<sup>5)</sup> and improved thereafter was used to obtain the values  $X$ ,  $Y$ , and  $\theta_{\text{ex}}$ . This program determines the above three parameters and the value of damping parameter,  $\log_{10}2\alpha$ , for the theoretical curve-of-growth under the condition that the sum of the squares of the differences in the abscissa of lines between the theoretical and observed curves takes the minimum value. In this program, a gradient of the theoretical curve-of-growth for the ordinate of a line is taken into account as a weight for the least-squares solution so that the lines on the linear and damping parts of the curve-of-growth are given heavier weight than those on the flat part of the curve, because the latter lines gives a larger difference between theoretical and observed curve-of-growth for the same value of error in the ordinate. The above four parameters were obtained for FeI and FeII lines of the relevant stars and the sun, respectively.

Secondly, the following values were calculated by the following equations from the four parameters obtained for FeI and FeII lines. In these equations,  $[Q]$  means the logarithmic difference between  $Q$  values for the relevant star and that of the sun,  $\log_{10}Q_{\text{star}} - \log_{10}Q_{\text{the sun}}$ .

$$[P_e] = \Delta X - \Delta X^+ - 2.5 [\theta_{\text{ion}}], \quad (1)$$

where  $P_e$  and  $\theta_{\text{ion}}$  are the electron pressure and the reciprocal ionization temperature, respective, and  $\Delta X$  and  $\Delta X^+$  are the differences of  $X$  values between the relevant stars and the sun for the neutral lines and singly-ionized lines of the same element, respectively. In the above equation, the value of  $[\theta_{\text{ion}}]$  is calculated by the following equation.

$$[\theta_{\text{ion}}] = \log_{10}[\{0.98 + (\Delta\theta_{\text{I}} + \Delta\theta_{\text{II}})/2\}/0.98], \quad (2)$$

where  $\Delta\theta_{\text{I}}$  and  $\Delta\theta_{\text{II}}$  are the differences of the  $\theta_{\text{ex}}$  values between the relevant star and the sun for neutral lines and singly-ionized lines, respectively. In the above equation, the ionization temperature of the sun is taken to be 0.98 after Cayrel and Jugaku (1963)<sup>6)</sup>. The microturbulence velocity,  $\xi_{\text{mi}}$ , is calculated by the following equation,

$$\xi_{\text{mi}} = (V_D^2 - V_{\text{th}}^2)^{1/2}, \quad (3)$$

where  $V_{\text{th}}$  means the thermal velocity and it is calculated by the following equation,

$$V_{\text{th}} = 0.01726 \times (5040/\theta_{\text{ion}})^{1/2}. \quad (4)$$

The  $V_D$  value is calculated by the following equation,

$$V_D = 1.591 \times 10^{[V_D]}. \quad (5)$$

In the above equations, the  $\xi_{\text{mi}}$  value of the sun is taken to be 1.0km/s and it is assumed that the thermal temperature is equal to the ionization temperature. The  $[V_D]$  value is derived from the difference in  $Y$  values between the sun and the relevant star. In the above derivation it is assumed that the  $Rc$  value of the

relevant star is equal to that of the sun.

Thirdly, the  $X$  values of the elements other than Fe were obtained from the observed curves-of-growth and the theoretical curve-of-growth. The theoretical curve-of-growth other than Fe was obtained assuming that the microturbulent velocity and the excitation temperature for the element are equal to those for Fe. It was also assumed that the  $\log_{10}2\alpha$  value for the element is equal to that for Fe. In the calculation of the  $V_D$  value for the theoretical curve-of-growth for the element, the difference in the thermal velocity due to the difference in an atomic weight was also taken into account.

The relative abundance of the element M,  $[M/H]$ , is calculated from the following equation;

$$[M/H] = \Delta X + 0.75\Delta\theta_I - [\theta_{\text{ion}}] - [x] + [u_{\text{II}}], \quad (7)$$

for neutral lines, and the following equation;

$$[M/H] = \Delta X^+ + 0.75\Delta\theta_{\text{II}} + 1.5[\theta_{\text{ion}}] + [P_e] - [x] + [u_{\text{II}}] \quad (8)$$

for singly-ionized lines, where  $x$  is the degree of single ionization and  $u_{\text{II}}$  is the partition functions of a singly-ionized atom. In the calculation of  $x$  and  $u_{\text{II}}$ , the following value of  $P_e$  is taken,

$$\log_{10} P_e = 0.45 + [P_e]. \quad (9)$$

In the above equation, the  $\log_{10} P_e$  value of the sun is taken to be 0.45 after Cayrel and Jugaku (1963)<sup>6)</sup>. The  $[Fe/H]$  values were also calculated from the equation (7) or from the equation (8).

Lastly, logarithmic difference in surface gravity,  $[g]$  is calculated by the following equation,

$$[g] = [P_{\text{H}}] + [P_e] + 1.9 \cdot (\Delta\theta_I + \Delta\theta_{\text{II}})/2 - [\tau] + [3X+1], \quad (10)$$

where  $P_{\text{H}}$  is the partial pressure of hydrogen and  $\tau$  is the mean optical depth of the formation of absorption lines and  $X$  is the mass fraction of hydrogen. The above equation is derived from the hydrostatic equation by Catchpole et al. (1967)<sup>7)</sup>. We have assumed that  $[\tau] = -0.10$  when the integrated sunlight is compared with the center of the solar disk and that  $[3X+1] = 0$ . The  $[P_{\text{H}}]$  value is calculated from the ionization equation

$$[P_{\text{H}}] = [P_e] - [x_{\text{H}} + (\text{Mg}/\text{H})_{\text{s}} 10^{[\text{Mg}/\text{H}]} x_{\text{Mg}} + (\text{Si}/\text{H})_{\text{s}} 10^{[\text{Si}/\text{H}]} x_{\text{Si}} + (\text{Fe}/\text{H})_{\text{s}} 10^{[\text{Fe}/\text{H}]} x_{\text{Fe}}], \quad (11)$$

where  $M/H$  is the number ratio of the element M to hydrogen and  $x$  is the degree of single ionization. In the above equation, the subscript attached to  $(M/H)$  means the  $M/H$  value of the sun, and the subscript of a chemical symbol attached to  $x$  means the  $x$  value of the element. In the above equation, it is assumed that the main donors of free electrons are Mg, Si, and Fe.

### III. The Results for U Mon and RV Tau

We obtained the equivalent widths for U Mon and RV Tau. We used the values listed in the table by Moore et al. (1966)<sup>8)</sup> as the equivalent widths for the sun. We used the values listed in the tables by Thevenin (1989)<sup>1)</sup> and Thevenin (1990)<sup>2)</sup> as the  $\log_{10}gf$  values. We used the values listed in the Chronological Scientific Tables (2010)<sup>9)</sup> for the ionization potentials and the atomic weights of the analyzed elements. We used  $H\beta$  line of hydrogen and  $D_1$  and  $D_2$  lines of sodium for the measurement of radial velocity of the star analyzed. The radial velocities measured were used for the calculation of the Doppler shifts of absorption lines and the Doppler shifts were used the identification of absorption lines.

#### III-1 U Mon

U Mon belongs to the RVb group and the group A. We obtained the following results for U Mon. We obtained  $-0.62$  and  $-2.50$  as the  $\log_{10}2\alpha$  value from FeI and FeII lines, respectively. We obtained  $0.13$  and  $0.10$  as the  $\Delta\theta_I$  and  $\Delta\theta_{\text{II}}$  values, respectively, and we obtained  $0.12$  as the  $\Delta\theta_{\text{ion}}$  value. We obtained  $4.0\text{km/s}$  and  $6.1\text{km/s}$  as the  $\xi_{\text{mi}}$  values from FeI and FeII lines, respectively. We obtained  $-2.0$  and  $-3.3$  as the  $[P_e]$  and  $[g]$  value, respectively. We obtained  $-0.89 \pm 0.17$  as the relative abundance,  $[Fe/H]$ .

We obtained the relative abundance,  $[M/H]$ , of 20 elements. We list the relative abundance,  $[M/H]$ , of U Mon in table 1.

For the elements, Si, Sc, Ti, V, Cr, and Fe, both neutral and singly-ionized lines were used to obtain the relative abundance. The relative abundances,  $[M/H]$ , for these elements are the weighted means of values from neutral and singly-ionized lines. The weight are taken from the probable errors of the relative abundances and the weighted mean value,  $[M/H]$ , was calculated by the following equation;

$$[M/H] = ([M/H]_{\text{I}}/pe_{\text{I}}^2 + [M/H]_{\text{II}}/pe_{\text{II}}^2)/(1/pe_{\text{I}}^2 + 1/pe_{\text{II}}^2), \quad (12)$$

and the probable error,  $pe$ , was calculated by the following equation;

$$pe = 0.6745 \times \{([M/H]_{\text{I}} - [M/H])^2/pe_{\text{I}}^2 + ([M/H]_{\text{II}} - [M/H])^2/pe_{\text{II}}^2\} / (1/pe_{\text{I}}^2 + 1/pe_{\text{II}}^2). \quad (13)$$

In the above two equations,  $[M/H]_{\text{I}}$  and  $[M/H]_{\text{II}}$  mean the  $[M/H]$  values from the neutral and singly-ionized lines, respectively, and  $pe_{\text{I}}$  and  $pe_{\text{II}}$  mean the probable errors for  $[M/H]_{\text{I}}$  and  $[M/H]_{\text{II}}$ , respectively.

The abundance of U Mon was obtained by Luck and Bond (1989)<sup>10)</sup>, Klochkova and Panchuk (1998)<sup>11)</sup>, Giridhar et al. (2000)<sup>12)</sup>, and Taguchi (2007)<sup>13)</sup>. Luck

**Table 1** The relative abundance of U Mon,  $[M/H]$ , which are the mean values from the neutral and singly-ionized lines, respectively, and Prob.Er. means the probable error. The  $[M/H]$  values are calculated according to the equation (12) the probable errors are calculated according to the equation (13), when both neutral and singly-ionized lines were measured.

|    | No. or Neutrsa Line | prob. Er. | No. or Ion Line | prob. Er. | $[M/H]$ | prob.Er |
|----|---------------------|-----------|-----------------|-----------|---------|---------|
| Na | 2                   | 0.125     | 0               | 0         | -0.379  | 0.125   |
| Mg | 2                   | 0.07      | 0               | 0         | -0.917  | 0.070   |
| Si | 8                   | 0.034     | 2               | 0.05      | -0.809  | 0.060   |
| Ca | 7                   | 0.078     | 0               | 0         | -0.932  | 0.078   |
| Sc | 2                   | 0.167     | 7               | 0.17      | -0.546  | 0.238   |
| Ti | 3                   | 0.18      | 5               | 0.202     | -0.657  | 0.271   |
| V  | 1                   | 0         | 2               | 0.183     | -1.071  | 0.183   |
| Cr | 4                   | 0.077     | 6               | 0.035     | -0.854  | 0.085   |
| Mn | 5                   | 0.104     | 0               | 0         | -1.161  | 0.104   |
| Fe | 58                  | 0.092     | 13              | 0.148     | -0.889  | 0.174   |
| Co | 2                   | 0.103     | 0               | 0         | -1.489  | 0.103   |
| Ni | 11                  | 0.086     | 0               | 0         | -0.845  | 0.086   |
| Cu | 1                   | 0         | 0               | 0         | -0.861  | 0.000   |
| Zn | 3                   | 0.137     | 0               | 0         | -0.702  | 0.137   |
| Y  | 0                   | 0         | 3               | 0.042     | -0.808  | 0.042   |
| Zr | 0                   | 0         | 1               | 0         | -0.775  | 0.000   |
| La | 0                   | 0         | 4               | 0.129     | -0.913  | 0.129   |
| Ce | 0                   | 0         | 2               | 0.052     | -0.937  | 0.052   |
| Nd | 0                   | 0         | 6               | 0.075     | -0.787  | 0.075   |
| Sm | 0                   | 0         | 1               | 0         | -0.748  | 0.000   |

and Bond (1989)<sup>10)</sup>, Klochkova and Panchuk (1998)<sup>11)</sup>, Giridhar et al. (2000)<sup>12)</sup>, and Taguchi (2007)<sup>13)</sup> analyzed the spectra observed at the pulsational phase of 0.26, 0.49, 0.30 and 0.50 respectively. The  $[Fe/H]$  values obtained by them are -0.83, -0.70, -0.79, and -0.75, respectively, for Luck and Bond (1989)<sup>10)</sup>, Klochkova and Panchuk (1998)<sup>11)</sup>, Giridhar et al. (2000)<sup>12)</sup>, and Taguchi (2007)<sup>13)</sup>. The relative abundances,  $[M/Fe]$ , obtained by them are listed in table 2, together with our values. The relative abundance,  $[M/Fe]$ , is calculated as the difference between  $[M/H]$  and  $[Fe/H]$ .

We obtained  $0.13 \pm 0.23$  and  $0.10 \pm 0.04$  as the  $\Delta\theta_I$  and  $\Delta\theta_{II}$  values, respectively, and we obtained 4.0km/s and 5.1km/s as the  $\xi_{mi}$  values from FeI and FeII lines, respectively. We obtained -2.0 and -3.3 as the  $[Pe]$  and  $[g]$  value, respectively. We obtained  $-0.89 \pm 0.17$  as the  $[Fe/H]$  value, which was obtained as the mean value of the values from FeI and FeII. Our  $[Fe/H]$  value is in good agreement with the other results, and it indicates that U Mon is a metal poor stars.

The other values, especially, the values for the microturbulent velocity,  $[Pe]$ , and  $[g]$ , indicate that U Mon is a supergiant. This result is also indicated by the low dispersion spectrograms and by the atmospheric parameters obtained by the other analyses.

For example, Luck and Bond (1989)<sup>10)</sup> obtained 0.31

as the  $\Delta\theta_{eff}$  value, where  $\Delta\theta_{eff}$  value is the difference in the reciprocal effective temperature. They obtained 5.0km/s as the  $\xi_{mi}$  value. They obtained -5.2 as the  $[g]$  value. Klochkova and Panchuk (1998)<sup>14)</sup> obtained 0.13, 6.0km/s, and -4.4 as the  $\Delta\theta_{eff}$ ,  $\xi_{mi}$ , and the  $[g]$  values, respectively. Giridhar et al. (2000)<sup>12)</sup> obtained 0.14, 2.5km/s, and -4.4 as the  $\Delta\theta_{eff}$ ,  $\xi_{mi}$ , and the  $[g]$  values, respectively. Finally, Taguchi (2007)<sup>16)</sup> obtained 0.24, 0.14, 3.8km/s, and -2.6 as the  $\Delta\theta_I$ ,  $\Delta\theta_{II}$ ,  $\xi_{mi}$ , and the  $[g]$  values, respectively.

Table 2 shows that many our values of  $[M/Fe]$  do not differ markedly from those of the other results. In table 2, our values subscripted corrected mean that the values are corrected according to our correction. This correction is made in order to take account of the systematic differences between the values by the curve-of-growth analysis and the values by the fine analysis. The comparison of the values between the curve-of-growth analysis and the fine analysis and the method of the correction are described in the appendix. In general, our corrected values do not improve the differences between our values and the other values. They rather increase the differences. Our values not corrected for the difference give the largest values for  $[Sc/Fe]$ ,  $[Ni/Fe]$ ,  $[Y/Fe]$  and  $[Ce/Fe]$ , and they give the smallest values for  $[Si/Fe]$  and

**Table 2** The comparison of the relative abundance for U Mon. Our Values subscribed cr mean that our values are corrected according to our correction.

|    | Klochko and Panchuk (1998) <sup>11)</sup> | Giridher, Lambert, and Gonzalez (2000) <sup>2)</sup> | This Study |        |
|----|-------------------------------------------|------------------------------------------------------|------------|--------|
|    | [M/Fe]                                    | [M/Fe]                                               | [M/Fe]cr   | [M/Fe] |
| C  | +0.77                                     | +0.61                                                | ...        | ...    |
| N  | ...                                       | ...                                                  | ...        | ...    |
| Na | +0.53                                     | +0.45                                                | +0.32      | +0.51  |
| Mg | -0.02                                     | +0.16                                                | -0.33      | -0.03  |
| Al | +0.04                                     | +0.04                                                | ...        | ...    |
| Si | +0.18                                     | +0.34                                                | -0.13      | +0.08  |
| Ca | -0.02                                     | -0.17                                                | -0.26      | -0.04  |
| Sc | -0.20                                     | -0.18                                                | +0.44      | +0.34  |
| Ti | +0.18                                     | +0.09                                                | +0.17      | +0.23  |
| V  | -0.56                                     | +0.13                                                | +0.25      | -0.18  |
| Cr | +0.00                                     | +0.07                                                | +0.23      | +0.04  |
| Mn | -0.17                                     | -0.47                                                | -0.19      | -0.27  |
| Co | ...                                       | +0.12                                                | +0.10      | -0.60  |
| Ni | ...                                       | -0.14                                                | +0.08      | +0.04  |
| Zn | +0.20                                     | +0.08                                                | +0.28      | +0.19  |
| Y  | -0.26                                     | -0.23                                                | -0.03      | +0.08  |
| Ba | ...                                       | ...                                                  | ...        | ...    |
| Ce | -0.47                                     | -0.29                                                | -1.05      | -0.05  |
| Nd | -0.55                                     | +0.11                                                | +0.03      | +0.10  |

[Co/Fe]. On the other hand, our values corrected for the difference give the largest values for [Sc/Fe], [V/Fe], [Cr/Fe], [Ni/Fe], [Zn/Fe] and [Y/Fe]. and they give the smallest values for [Na/Fe], [Si/Fe], [Ca/Fe] and [Ce/Fe].

It seems that the [M/Fe] values are not so affected by systematic errors as the [M/H] values. In the following, the [M/Fe] values are mainly used in order to judge the validity of the above three mechanisms. Moreover, our [M/Fe] values not corrected for the difference are used for the judgement.

There is not a clear correlation between our [M/H] values and the 50% concentration temperatures,  $T_c$ , i.e., the [M/H] values do not show a clear decrease with the increase of the  $T_c$  values, where the 50% concentration temperature were taken from the table by Lodders (2003)<sup>14)</sup>. Lodders (2003)<sup>14)</sup> calculated the 50% condensation temperatures assuming a solar-system composition gas and a total pressure of  $10^{-4}$  bar.

For example, the [Na/Fe] and [Zn/Fe] give plus values, where these elements have lower  $T_c$  values than that for Fe. But the [Sc/Fe], [Ti/Fe] and [Y/Fe] give plus values, where these elements have larger  $T_c$  values than that for Fe. These results indicate that our [M/Fe] values do not correlate with the  $T_c$

values.

According to the first ionization mechanism, the smaller the first ionization potentials are, the larger the degrees of overionization become. Therefore, the smaller the first ionization potentials are, the smaller are the [M/Fe] values derived from neutral lines. The first ionization potential of Fe is equal to 7.90eV. Our [M/Fe] values show that this correlation is not indicated. For example, the [Mn/Fe] and [Zn/Fe] values give a minus and a plus value respectively, where the first ionization potentials of Mn is lower than 7.90eV and that of Zn is larger than 7.90eV. This result obeys the first ionization mechanism. On the other hand, both of the [Na/Fe] and [Ni/Fe] values give plus values, where the first ionization potentials of both of the elements are lower than 7.90eV. This result disobeys the first ionization mechanism.

According to the second ionization mechanism, the [M/H] values whose second ionization potentials are smaller than 13.60eV are smaller than the [M/H] values whose second ionization potentials are larger than 13.60eV. The second ionization potential of Fe is equal to 16.19eV. Therefore, the [M/Fe] values whose second ionization potentials are smaller than 13.60eV should take minus values. This correlation is not indicated. All of the three elements whose [M/Fe] values

are derived from singly-ionized lines have second ionization potentials smaller than 13.60eV. The  $[\text{Ce}/\text{Fe}]$  value takes minus value, while the  $[\text{Y}/\text{Fe}]$  and  $[\text{Nd}/\text{Fe}]$  values take plus values.

Our results are summarized that the abundance of U Mon is not affected by the three mechanism above described.

### III-2 RV Tau

RV Tau belongs to the RVb group and the group A. We analyzed the spectrum of RV Tau by the same method as that for U Mon. We analyzed the spectrum obtained at the pulsational phase of 0.49. We could not obtain  $\Delta\theta_{\text{II}}$  value, because we could use only three Fe II lines. Therefore, we adopted the  $\Delta\theta_{\text{I}}$  value as the  $\Delta\theta_{\text{II}}$  and  $\Delta\theta_{\text{ion}}$  values and we adopted the  $\xi_{\text{mi}}$  values from FeI as the  $\xi_{\text{mi}}$  values from FeII. We obtained 0.39 as the  $\Delta\theta_{\text{I}}$  value. We obtained 2.6km/s as the  $\xi_{\text{mi}}$  values from FeI and FeII lines, respectively. We obtained  $-3.46$  as the  $[\text{g}]$  value. We obtained  $-0.32$  as the  $[\text{Fe}/\text{H}]$  value.

We also obtained the relative abundance,  $[\text{M}/\text{H}]$  of 14 elements. We list the relative abundance,  $[\text{M}/\text{H}]$ , of RV Tau in table 3. As is shown in table 3, we could use both neutral and singly-ionized lines only for Fe and Cr.

The abundance of RV Tau was obtained by Klochkova and Panchuk (1998)<sup>11)</sup>, and Giridhar et al. (2000)<sup>12)</sup>, and Yoshioka and Matsuda (2014)<sup>15)</sup>. Klochkova and Panchuk (1998)<sup>11)</sup> analyzed the spectra observed at the pulsational phase of 0.26 and 0.78, respectively. Klochkova and Panchuk (1998)<sup>11)</sup> obtained 0.07 and 0.09 as the  $[\text{Fe}/\text{H}]$  values, respectively, for the phase 0.26 and 0.78. Giridhar et al. (2000)<sup>12)</sup> analyzed the spectra observed at the pulsational phase of 0.56 and they obtained by  $-0.41$  as the  $[\text{Fe}/\text{H}]$  value. Yoshioka and Matsuda (2014)<sup>15)</sup> analyzed the spectra observed at the pulsational phase of 0.37 and obtained  $-1.27$  as the  $[\text{Fe}/\text{H}]$  value.

Our  $[\text{Fe}/\text{H}]$  value is in good agreement with that by Giridhar et al. (2000)<sup>12)</sup>. On the other hand, the  $[\text{Fe}/\text{H}]$  values by Klochkova and Panchuk (1998)<sup>11)</sup> are much larger than our value and the  $[\text{Fe}/\text{H}]$  value by Yoshioka and Matsuda (2014)<sup>15)</sup> is much smaller than our value. These results indicate that RV Tau is a normal star or a slightly metal poor star, except for the result by Yoshioka and Matsuda (2014)<sup>15)</sup> where they indicate that RV Tau is a metal poor star.

The other values, especially, the values for the microturbulent velocity and  $[\text{g}]$ , indicate that RV Tau is a supergiant. For example, Klochkova and Panchuk (1998)<sup>11)</sup> obtained 5km/s and 4km/s as the  $\xi_{\text{mi}}$  values, respectively, for the phase 0.26 and 0.78. They ob-

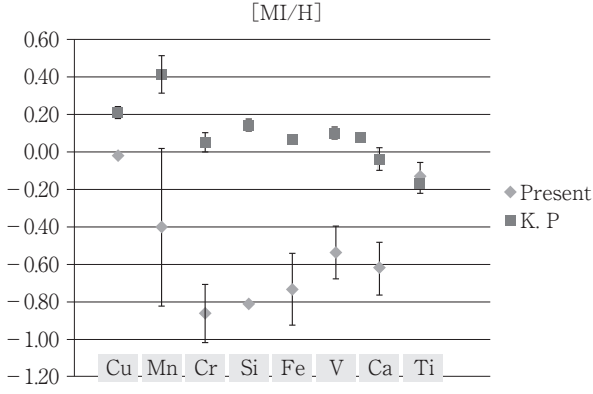
tained  $-3.4$  and  $-4.2$  as the for the phase 0.26 and 0.78. Giridhar et al. (2000)<sup>12)</sup> obtained 3km/s and  $-4.4$  as the  $\xi_{\text{mi}}$  value and the  $[\text{g}]$  value, respectively. Yoshioka and Matsuda (2014)<sup>15)</sup> obtained 2.9km/s and  $-2.6$  as the  $\xi_{\text{mi}}$  value and the  $[\text{g}]$  value, respectively.

Many our  $[\text{M}/\text{Fe}]$  values differ from those of the other three observations. For example, The  $[\text{Mn}/\text{Fe}]$  values for them have positive signs, while our value has a negative sign, though the differences are not large. The  $[\text{Si}/\text{Fe}]$  values for them have positive signs, while our value has a negative sign, and the difference is large. The  $[\text{Ni}/\text{Fe}]$  value for Giridhar et al. (2000)<sup>12)</sup> has a positive sign, while our value has a negative sign, and the difference is large. The  $[\text{Ti}/\text{Fe}]$  values for them have negative signs, while our value has positive sign, though the differences are not large. The  $[\text{Sc}/\text{Fe}]$  values for Giridhar et al. (2000)<sup>12)</sup> and Yoshioka and Matsuda (2014)<sup>15)</sup> have positive signs, while our value has a negative sign, and the differences are large. On the other hand, the  $[\text{Sc}/\text{Fe}]$  values for Klochkova and Panchuk (1998)<sup>11)</sup> has a negative signs.

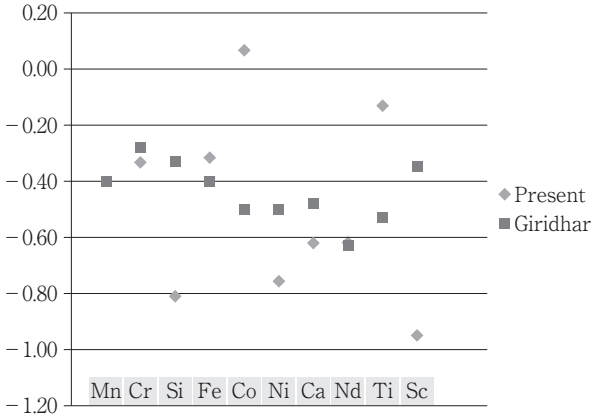
Figure 1 shows the comparison of our  $[\text{M}/\text{H}]_{\text{I}}$  values and those by Klochkova and Panchuk (1998)<sup>11)</sup>, where their values are the values for the phase of 0.26. As is shown in this figure, except for Ti, our values are smaller than those by them and the differences are large. Figure 2 shows the comparison of our  $[\text{M}/\text{H}]$  values and those by Giridhar et al. (2000)<sup>12)</sup>. As is shown in this figure, there is not a systematic difference between our values and those by them. But, scatter of our values with elements is larger than that by them. Figure 3 shows the comparison of our  $[\text{M}/\text{H}]_{\text{I}}$  values and those by Yoshioka and Matsuda (2014)<sup>15)</sup>. As is shown in this figure, our values are systematically larger than those by them. The above comparisons are summarized that our  $[\text{M}/\text{H}]$  values are intermediate between those by Yoshioka and Matsuda (2014)<sup>15)</sup> and those by Klochkova and Panchuk (1998)<sup>14)</sup>, and our values are near those by Giridhar et al. (2000)<sup>12)</sup>.

Figure 4 shows the correlation between our  $[\text{M}/\text{H}]$  values and the 50% concentration temperatures,  $T_{\text{c}}$ . Our values indicate that RV Tau is a metal poor star, as were indicated by Giridhar et al. (2000)<sup>12)</sup> and by Yoshioka and Matsuda (2014)<sup>15)</sup>. Our values slightly indicate that the  $[\text{M}/\text{H}]$  values decrease with the increase of the  $T_{\text{c}}$  values. But the correlation is not clear.

Table 3 indicates that there is not the correlation between our  $[\text{M}/\text{Fe}]$  values derived from neutral lines and the first ionization potentials. For example, the  $[\text{Si}/\text{Fe}]$  value gives a minus value, where Si is the only element that have the first ionization potential



**Figure 1** The comparison of our  $[M/H]_1$  values and those by Klochko and Panchuk (1998)<sup>11)</sup>. Our values and those by Klochko and Panchuk (1998)<sup>11)</sup> are indicated by filled diagonal small squares and by filled large squares, respectively.

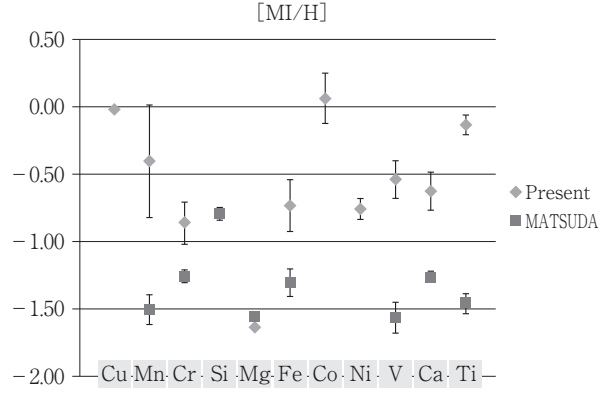


**Figure 2** The comparison of our  $[M/H]_1$  values and those by Giridhar et al. (2000)<sup>12)</sup>. Our values and those by Giridhar et al. (2000)<sup>12)</sup> are indicated by filled diagonal small squares and by filled large squares, respectively.

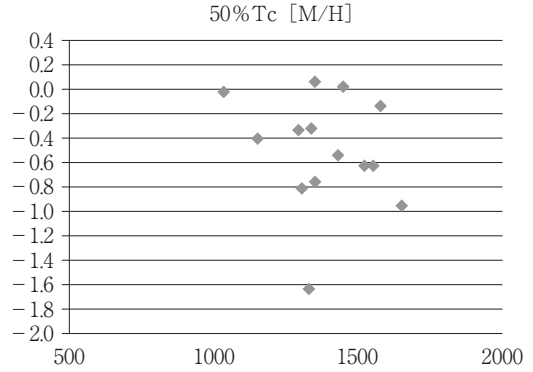
larger than 7.90eV.

Table 3 also indicates that there is not the correlation between our  $[M/Fe]$  values derived from singly-ionized lines and the second ionization potentials. For example, the  $[Nd/Fe]$  and  $[Sc/Fe]$  values have minus values, where the second ionization potentials of these elements are smaller than 13.60eV. However, the  $[Ba/Fe]$  value has a plus value, where the second ionization potential of Ba is lower than 13.60eV. Moreover, the  $[Cr/Fe]$  value is equal to 0.44 which is larger the probable error of this value, where the second ionization potential of Cr is nearly equal to that of Fe.

Our results are summarized that the abundance of RV Tau is not affected by the first ionization mechanism. Nor, is affected it by the second ionization one.



**Figure 3** The comparison of our  $[M/H]_1$  values and those by Yoshioka and Matsuda (2014)<sup>15)</sup>. Our values and those by Yoshioka and Matsuda (2014)<sup>15)</sup> are indicated by filled diagonal small squares and by filled large squares, respectively.



**Figure 4** The correlation between the relative abundance,  $[M/H]$ , and the 50% concentration temperature,  $T_c$ , for RV Tau. The ordinate is the  $[M/H]$  value and the abscissa is the 50% concentration temperature (K).

Our results indicates the sign of the dust-gas separation mechanism.

#### IV. Discussion

According to the results in the section III, we can conclude that the abundances of U Mon and RV Tau do not affected by the three proposed mechanisms, though that of RV Tau has a sign of the dust-gas separation mechanism.

According to Giridhar et al. (2000)<sup>12)</sup>, the RV Tau stars of the group B show the pattern of abundance ascribed to the dust-gas separation mechanism, but the stars of the group A show the abundance which are very largely unaffected by the dust-gas separation mechanism. There is a tendency that the effective temperature of the group A is lower that of the

**Table 3** The relative abundance for RV Tau  
 $[M/H]_{\text{I}}$  and  $[M/H]_{\text{II}}$  mean the  $[M/H]$  values from the neutral and singly-ionized lines, respectively, and Prob.Err. means the probable error.  
 $[M/Fe]_{\text{I}}$  and  $[M/Fe]_{\text{II}}$  mean the  $[M/Fe]$  values from the neutral and singly-ionized lines, respectively.

| element   | n  | $[M/H]_{\text{I}}$  | Prob. Err | $[M/H]_{\text{I}}$  | Prob. Err |
|-----------|----|---------------------|-----------|---------------------|-----------|
| Fe ( I )  | 62 | -0.731              | 0.191     |                     |           |
| Ca ( I )  | 5  | -0.622              | 0.140     | 0.109               | 0.237     |
| Co ( I )  | 3  | 0.065               | 0.186     | 0.796               | 0.267     |
| Cr ( I )  | 5  | -0.860              | 0.155     | -0.129              | 0.246     |
| Cu ( I )  | 1  | -0.020              | 0.000     | 0.711               | 0.191     |
| Me ( I )  | 1  | -1.632              | 0.000     | -0.901              | 0.191     |
| Mn ( I )  | 5  | -0.402              | 0.418     | 0.329               | 0.460     |
| Ni ( I )  | 14 | -0.757              | 0.075     | -0.026              | 0.205     |
| Sl ( I )  | 1  | -0.810              | 0.000     | -0.079              | 0.191     |
| Ti ( I )  | 4  | -0.132              | 0.073     | 0.599               | 0.204     |
| V ( I )   | 5  | -0.537              | 0.140     | 0.194               | 0.237     |
|           |    |                     |           |                     |           |
| element   | n  | $[M/H]_{\text{II}}$ | Prob. Err | $[M/H]_{\text{II}}$ | Prob. Err |
| Fe ( II ) | 3  | -0.281              | 0.056     |                     |           |
| Ba ( II ) | 1  | 0.025               | 0.000     | 0.306               | 0.056     |
| Cr ( II ) | 2  | 0.155               | 0.323     | 0.436               | 0.328     |
| Nd ( II ) | 3  | -0.619              | 0.106     | -0.338              | 0.120     |
| Sc ( II ) | 3  | -0.950              | 0.214     | -0.669              | 0.221     |

group B. They proposed that the deeper convective envelope of the group A with a cooler atmosphere dilutes anomalies resulting from dust-gas separation. Our results indicate that the group A stars, U Mon and RV Tau, do not show a conspicuous pattern of abundance by the dust-gas separation, which confirms the proposition by Giridhar et al. (2000)<sup>12)</sup>.

According to Giridhar et al. (2000)<sup>12)</sup>, the post-AGB stars including the RV Tau stars with an intrinsic metallicity  $[Fe/H]_0 < -1$ , as assessed from S and Zn abundances, are not subject to effects of a dust-gas separation. Our mean values of  $[S/H]$  and  $[Zn/H]$  are equal to  $-0.82$  for U Mon. Although we could not obtain  $[S/H]$  value nor  $[Zn/H]$  value, the  $[Fe/H]_0$  value seems to be higher than  $-1$ , because the  $[Fe/H]$  value is higher than  $-1$ . Both the  $[Fe/H]_0$  values for U Mon and RV Tau are higher than the boundary of the effectiveness of the dust-gas separation. These values contradict the above result that the U Mon and RV Tau do not show a conspicuous pattern of abundance by the dust-gas separation.

On the other hand, observational errors of some elements are large for our results and there is a large systematic difference, particularly for the  $[Fe/H]$  values, between our results and other results analyzed before our results. As the differences among the other results are large, the cause of these differences is not

necessarily the error of our results. But our analysis need to be reexamined. We are going to reanalyze U Mon by a different process of the differential curve-of-growth analysis.

## Appendix

We have compared the results by fine analyses and coarse analyses done before for AC Her, HD33579,  $\alpha$  Cyg,  $\epsilon$  Vir, and HD187203. AC Her is a RV Tauri variable which belongs to the RVb group and the group B: HD33579 is an early type supergiant with the spectral type of A3Ia+:  $\alpha$  Cyg is also an early type supergiant with the spectral type of A2Iae:  $\epsilon$  Vir is a solar-type giant with the spectral type of G8III: HD187203 is also a solar-type supergiant of the spectral type of F8Ib. We have compared the  $[M/Fe]$  values for these stars.

For AC Her we have compared the  $[M/Fe]$  values obtained by Giridhar, Lambert, and Gonzalez (1998)<sup>16)</sup> and Yoshioika (1979)<sup>17)</sup>, where they analyzed the spectra around the phase of 0.47. Yoshioika (1979)<sup>17)</sup> analyzed the spectra by a coarse analysis and Giridhar, Lambert, and Gonzalez (1998)<sup>16)</sup> analyzed the spectra by a fine analysis. For HD33579 we have compared the values obtained by Wolf (1971)<sup>18)</sup>, Wares, Ross and Aller (1968)<sup>19)</sup>, and Przybylski (1967)<sup>20)</sup>.

**Table 4** The comparison in  $[M/Fe]$  values between fine and coarse analyses. The  $[M/Fe]$  values by fine analyses minus those by coarse analyses are listed for the five stars. The correction coefficients which are mean values for the above differences also are listed in the last column.

|    | AC Her                     | HD33579                    | $\alpha$ Cyg               | $\varepsilon$ Vir          | HD187203                   | Correction                |            |
|----|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------------|------------|
|    | $[M/Fe]_F$<br>– $[M/Fe]_C$ | $[M/Fe]_F$<br>– $[M/Fe]_C$ | $[M/Fe]_F$<br>– $[M/Fe]_C$ | $[M/Fe]_F$<br>– $[M/Fe]_C$ | $[M/Fe]_F$<br>– $[M/Fe]_C$ | Correction<br>coefficient | Error      |
| C  | + 0.17                     | ...                        | ...                        | ...                        | + 0.27                     | + 0.22                    | $\pm 0.07$ |
| N  | ...                        | ...                        | + 0.28                     | ...                        | ...                        | + 0.28                    |            |
| Na | – 0.49                     | ...                        | ...                        | + 0.11                     | ...                        | – 0.19                    | $\pm 0.42$ |
| Mg | – 0.32                     | – 0.63                     | – 0.39                     | + 0.13                     | ...                        | – 0.30                    | $\pm 0.42$ |
| Al | ...                        | + 0.70                     | + 0.11                     | ...                        | ...                        | + 0.41                    | $\pm 0.42$ |
| Si | – 0.46                     | – 0.74                     | – 0.03                     | + 0.02                     | + 0.16                     | – 0.21                    | $\pm 0.38$ |
| Ca | – 0.43                     | – 0.62                     | – 0.19                     | + 0.10                     | + 0.05                     | – 0.22                    | $\pm 0.31$ |
| Sc | + 0.09                     | + 0.56                     | – 0.25                     | ...                        | – 0.02                     | + 0.10                    | $\pm 0.34$ |
| Ti | – 0.34                     | + 0.15                     | – 0.28                     | + 0.12                     | + 0.07                     | – 0.06                    | $\pm 0.23$ |
| V  | + 0.56                     | + 0.61                     | ...                        | + 0.12                     | ...                        | + 0.43                    | $\pm 0.27$ |
| Cr | – 0.03                     | – 0.20                     | + 1.13                     | + 0.12                     | – 0.09                     | + 0.19                    | $\pm 0.54$ |
| Mn | + 0.49                     | – 0.37                     | ...                        | + 0.12                     | ...                        | + 0.08                    | $\pm 0.43$ |
| Co | + 0.70                     | ...                        | ...                        | ...                        | ...                        | + 0.70                    |            |
| Ni | – 0.40                     | + 0.57                     | ...                        | ...                        | – 0.04                     | + 0.04                    | $\pm 0.49$ |
| Zn | + 0.09                     | ...                        | ...                        | ...                        | ...                        | + 0.09                    |            |
| Y  | – 0.07                     | ...                        | ...                        | ...                        | – 0.15                     | – 0.11                    | $\pm 0.06$ |
| Ba | – 0.12                     | ...                        | ...                        | ...                        | ...                        | – 0.12                    |            |
| Ce | – 1.00                     | ...                        | ...                        | ...                        | ...                        | – 1.00                    |            |
| Nd | – 0.07                     | ...                        | ...                        | ...                        | ...                        | – 0.07                    |            |

Wolf (1971)<sup>18)</sup> analyzed the spectra by a fine analysis, and Wares, Ross and Aller (1968)<sup>19)</sup> and Przybylski (1967)<sup>20)</sup> analyzed by coarse analyses. For  $\alpha$  Cyg we have compared the values obtained by Groth (1961)<sup>21)</sup>, who analyzed this star both by a fine and by a coarse analyses. For  $\varepsilon$  vir we have compared the values obtained by Cayrel and Cayrel (1963)<sup>22)</sup>, who also analyzed both by a fine and by a coarse analyses. For HD187203 we compared the values obtained by Yoshioka et.al. (2005)<sup>23)</sup>. They analyzed both by a fine analysis and by a coarse analysis.

Table 4 lists the differences between the  $[M/Fe]$  values obtained by fine and coarse analyses for the above five stars. We obtained the mean values of the differences, which also are listed in this table. We adopted these differences as the correction coefficient which gives the  $[M/Fe]$  value by a fine analysis from the  $[M/Fe]$  value by a coarse analysis.

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