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The Determination of Abundances of Two Stars RV Tauri Stars, AC Her and RV Tau

Kazuo YOSHIOKA・Toshimiti MATSUDA

２つのおうし座RV型変光星、ヘルクレス座AC星とおうし座TV星の化学組成の決定

吉　岡　一　男[1)]・松　田　利　通[2)]

ABSTRACT

We observed two RV Tauri variables, AC Her and RV Tau, and we determined the chemical abundance 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 with 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 correlation between the abundance relative to the sun and the condensation temperature for both of the stars that the [M/H] values decrease with the condensation temperature, thought the scatters are large, which indicates that the dust-gas separation mechanism prevails in both of the stars.

2）The above correlation of the group A star, RV Tau, is more conspicuous than that of the group B star, AC Her, which contradicts the results by Giridhar et al. (2000)[18)], 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 [S/H] and [Zn/H] for AC Her and RV Tau, the above result of 2）do not contradict the results by Giridhar et al. (2000)[18)], 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、AC Her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シェル分光器を用いて行い、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。整約はソフトウェアIRAFを用いて行った。

そして、次の結果が得られた。

[1)] 放送大学教授（「自然と環境」コース）
[2)] 放送大学大学院自然環境科学プログラム修士課程

1）両星とも太陽に相対的な元素量は、散らばりは大きいが、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少ない。この結果は、両星ともダスト・ガス凝縮が働いていることを示してる。
2）上述の相関は、AグループのRV Tauの方がBグループのAC Herよりも顕著である。これは、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)[18] の結果に反する。
3）AC HerとRV Tauの[S/H]と[Zn/H]の値によれば、2）の結果は、もともとの[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)[18] の結果には反しない。
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 potential 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 recombinate 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, 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 AC Her and U Mon, which belong to the RV Tauri variable. The data of these stars are listed in Table 1

Ⅱ. Observations

We have analyzed the spectra of AC Her and U Mon. 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

Table 1 The relative abundance of AC Her

The results obtained from neutral or singly-ionized lines							Mean value	
Element	No.of line	$[M/H]_{I}$	Prob.Er.	No.of line	$[M/H]_{II}$	Prob.Er.	[M/H]	Prob.Er.
Fe	59	−1.75	0.10	23	−1.81	0.32	−1.75	0.01
Na	4	−1.08	0.09				−1.08	0.09
Mg	3	−1.71	0.24				−1.71	0.24
Si	4	−1.46	0.09	2	−1.64	0.05	−1.61	0.05
S	2	−1.05	0.27				−1.05	0.27
Ca	11	−1.64	0.04				−1.64	0.04
Sc	3	−0.39	0.11	4	−2.05	0.04	−1.82	0.38
Ti	1	−1.11		3	−2.19	0.04	−2.09	0.22
V	3	−0.81	0.11	1	−1.29		−0.85	0.10
Cr	4	−1.98	0.11	6	−2.10	0.07	−2.06	0.04
Mn	4	−1.77	0.10				−1.77	0.10
Zn	2	−1.10	0.14				−1.10	0.14

$[M/H]_{I}$ and $[M/H]_{II}$ mean the [M/H] values from the neutral and singly-ionized lines, respectively, and Prob. Er. means the probable error. [M/H] means the $[M/H]_{I}$ value, when only neutral lines were measured. [M/H] means the mean value of $[M/H]_{I}$ and $[M/H]_{II}$ values calculated according to the equation (12), and the probable error is calculated according to the equation (13), when both neutral and singly-ionized lines were measured.

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 indicates that a shock wave passes the photosphere and LTE is not a good approximation. We selected the spectrum of AC Her which was taken on March 20, 2009 and the spectrum of RV Tau which was taken on November 23, 2009. Both of the spectra were taken at the phase between the primary light maximum and 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 Hα line nor Hγ line which give a bad influence in the measurement of equivalent widths of metallic lines.

Data reduction was carried out using standard technics 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)[1] and Thevenin (1990)[2]. The line list of the solar spectrum by Moore et al. (1966)[3] 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 θ_{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 θ_{ex} is the reciprocal excitation temperature, $5040/T_{ex}$ (T_{ex} is an excitation temperature). In the observed curve-of-growth, the $\log_{10}W/\lambda$ values are plotted in the ordinate and the $\log_{10}gf\lambda+\theta_{ex}\,\Delta\chi$ 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 $\log_{10}(Wc/2R_{C}V_{D}\lambda)$ values are plotted in the theoretical curve-of-growth, where c and V_D are the speed of light and the Dopper velocity, respectively ; R_C 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)[4] was used. The program made by Yoshioka (1987)[5] and improved thereafter was used to obtain the values X, Y, and θ_{ex}. This program determines the above three parameters and the value of damping parameter, $\log_{10}2a$, for the theoretical curve-of-growth under the condition that the sum of the squares of the differences 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 Fe I and Fe II 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 Fe I and Fe II lines. In these equations, $[Q]$ means the logarithmic difference between Q values for the relevant star and that of the sun, $\log_{10}Q_{star} - \log_{10}Q_{the\ sun}$.

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

where P_e and θ_{ion} are the electron pressuree and the reciprocal ionization temperature, respective, and ΔX and ΔX^+ 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 $[\theta_{ion}]$ is calculated by the following equation.

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

where $\Delta\theta_{I}$ and $\Delta\theta_{II}$ are the differences of the θ_{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)[6]. The micrturbulence velocity, ξ_{mi}, is calculated by the following equation,

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

where V_{th} means the thermal velocity and it is calculated by the following equation, (4)

$$V_{th} = 0.01726 \times (5040/\theta_{ion})^{1/2}. \quad (5)$$

The V_D value is calculated by the following equation,

$$V_D = 1.591 \times 10^{[V_D]}. \quad (6)$$

In the above equations, the ξ_{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 R_C 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 ;

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

for neutral lines, and the following equation ;

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

for singly-ionized lines, where x is the degree of single ionization and u_{II} is the partition functions of a singly-ionized atom. In the calculation of x and u_{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)[6]. 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,

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

where P_H is the partial pressure of hydrogen and τ 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)[7]. 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 $[P_H]$ value is calculated from the ionization equation

$$[P_H] = [P_e] - [x_H + (\mathrm{Mg/H})_S 10^{[\mathrm{Mg/H}]} x_{Mg} + (\mathrm{Si/H})_S 10^{[\mathrm{Si/H}]} x_{Si} + (\mathrm{Fe/H})_S 10^{[\mathrm{Fe/H}]} x_{Fe}], \quad (11)$$

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 AC Her and RV Tau

We obtained the equivalent widths for AC Her and RV Tau. We used the values listed in the table by Moore et al. (1966)[8] as the equivalent widths for the sun. We used the values listed in the tables by by Thevenin (1989)[9] and Thevenin (1990)[10] as the $\log_{10}gf$ values. We used the values listed in the Chronological Scientific Tables (2010)[11] for the ionization potentials and the atomic weights of the analyzed elements. We used Hβ 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 for the identification of absorption lines.

Ⅲ-1 AC Her

AC Her belongs to the RVa group and the group B. We obtained the following results for AC Her. We obtained −1.06 and −1.07 as the $\log_{10}2\alpha$ value from Fe I and Fe II lines, respectively. We obtained 0.09 and 0.06 as the $\Delta\theta_{I}$ and $\Delta\theta_{II}$ values, respectively, and we obtained 0.08 as the $\Delta\theta_{ion}$ value. We obtained 4.4km/s and 2.9km/s as the ξ_{mi} values from Fe I and Fe II lines, respectively. We obtained −1.95 and −3.4 as the [P_e] and [g] value, respectively. We obtained −1.75±0.01 as the relative abundance, [Fe/H].

We obtained the relative abundance, [M/H], of 12 elements. We list the relative abundance, [M/H], of AC Her in Table 1 together with the 50% concentration temperatures of the elements. The 50% concentration temperature were taken from the table by Lodders (2003)[12]. Lodders (2003)[12] calculated the 50% condensation temperatures assuming a solar-system composition gas and a total pressure of 10^{-4} bar.

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;

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

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

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

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

The abundance of AC Her was obtained by Yoshioka (1979)[13], Klochkova and Panchuk (1998)[14], Van Winkel et al. (1998)[15], and Giridhar et al. (1998)[16]. Giridhar et al. (1998)[16] analyzed the spectra observed at the pulsational phase of 0.47 and 0.70, respectively. The [Fe/H] values obtained by them are −1.18, −0.82, and −1.69, respectively, for Yoshioka (1979)[13], Klochkova and Panchuk (1998)[14], and Van Winkel et al. (1998)[15]. Giridhar et al. (1998)[16] obtained −1.3 and −1.4, respectively, for the phase 0.40 and 0.70. 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]. The [M/Fe] values by Giridhar et al. (1998)[16] are the mean values for the two phases.

Table 2 The Comparison of the relative abundance for AC Her

Rrelative abundance	Y	G	K	V	M
[Fe/H]	−1.18	−1.40	−0.82	−1.69	−1.75
[Na/Fe]	1.01	0.60	0.39	0.78	0.67
[Mg/Fe]	0.49	0.25	−0.26	0.37	0.04
[Si/Fe]	0.82	0.46	0.05	0.39	0.15
[S/Fe]		1.03	0.56	0.94	0.70
[Ca/Fe]	0.17	−0.08	−0.23	0.01	0.11
[Sc/Fe]	−0.46	−0.30	−0.31	−0.28	−0.07
[Ti/Fe]	0.01	−0.24	−0.31	−0.28	−0.33
[V/Fe]	−0.60	0.08	0.14		0.90
[Cr/Fe]	−0.05	−0.07	−0.03	0.06	−0.31
[Mn/Fe]	−0.20	0.40	0.01	0.08	−0.01
[Zn/Fe]	0.30	0.47	0.69	0.67	0.65

The uppercase letters Y, G, K, V, and M indicate the following capital letters of the investigators, respectively, Yoshioka (1979)[13], Giridhar et al. (1998)[16], Klochkova and Panchuk (1998)[14], Winkel et al. (1998)[15], and this work. The [M/H] values for Giridhar et a. (1998)[16] are mean values of the phase of 0.47 and 0.70.

Our values for the atmospheric parameters indicates that AC Her 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, Yoshioka (1979)[13] obtained 0.07 and 0.01 as the $\Delta\theta_{I}$ and $\Delta\theta_{II}$ values, respectively, and he obtained 3.0km/s and 4.7km/s as the ξ_{mi} values from Fe I and Fe II lines, respectively. He obtained −1.56 and −3.3 as the [P_e] and [g] value, respectively. These values, especially, the values for the microturbulent velocity, [P_e], and [g], are close to our values, and it confirmes that AC Her is a supergiant.

On the other hand, our value of [Fe/H] is lower than that those obtained by the other analyses. Especially, the value by Klochkova and Panchuk (1998)[14] is higher than our value by 0.93, though the difference between our value and that by Van Winkel et al. (1998)[15], which is 0.06, is small. This difference may be partly due to the difference in the surface temperature. For the same strength of absorption line, the lower surface temperature gives the lower [Fe/H] value. Our the $\Delta\theta_{I}$ and $\Delta\theta_{II}$ values are lowest among the above results. Furthermore, Klochkova and Panchuk (1998)[14] obtained the highest effective tem-

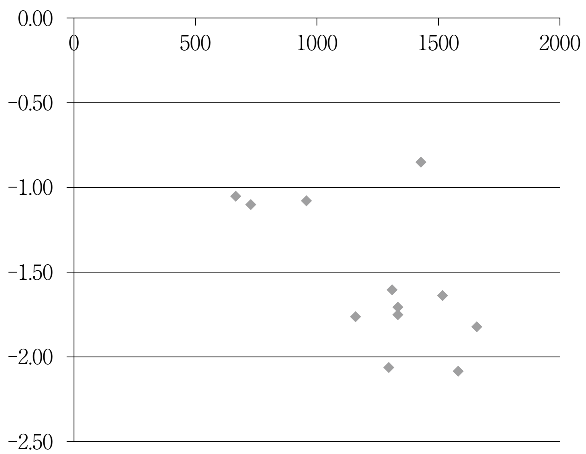

Fig. 1 The correlation between the relative abundance, [M/H], and the 50% concentration temperature, T_C, for AC Her. The ordinate is the [M/H] value and the abscissa is the the 50% concentration temperature.

perature whose value of $\Delta\theta$ is equal to -0.05.

Table 2 shows that our values of [M/Fe] do not differ markedly from those of the other results, except for Sc, V, and Cr. 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.

Table 1 shows that there is some correlation between [M/H] and the 50% concentration temperatures, T_C, i.e., the [M/H] values decrease with the increase of the T_C values. It is also shown in Figure 1. In this figure, the [V/H] value is dislocated from the correlation. The observational error of this value is large, and the correlation becomes clear, if this value is excluded. This correlation follows the prediction by the dust-gas separation mechanism.

Table 3 shows the correlation between the [M/Fe] values derived from the neutral lines and the first ionization potential. 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 the neutral lines. The first ionization potential of Fe is equal to 7.90eV. As is shown in Table 3, this correlation is not indicated. Table 3 shows that the first ionization mechanism does not affect the photospheric abundance of AC Her.

Table 4 shows the correlation between the [M/Fe] values derived from the singly-ionized lines and the second ionization potentials. 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 13.60eV should take minus values. As is shown in Table 4, the [V/Fe] and [Cr/Fe] values do not follow this correlation. Table 3 shows that the second ionization mechanism does not affect either the photospheric abundance of AC Her.

Table 3 The abundance of AC Her from neutral lines.

Element	[M/Fe]	Prob.Er.	The first ionization potential (eV)
Na	0.67	0.09	5.14
Mg	0.04	0.24	7.65
Si	0.29	0.05	8.15
S	0.69	0.27	10.36
Ca	0.11	0.04	6.11
Sc	1.36	0.38	6.56
Ti	0.63	0.22	6.83
V	0.94	0.10	6.75
Cr	−0.23	0.04	6.77
Mn	−0.02	0.10	7.43
Zn	0.64	0.14	9.39

The [M/Fe] values are calculated from [M/H] and [Fe/H] values both of which are obtained only from the neutral lines.

Table 4 The abundance of AC Her from singly-ionized lines.

Element	[M/Fe]	Prob.Er.	the second ionization potential (eV)
Si	0.17	0.32	16.35
Sc	−0.23	0.32	12.80
Ti	−0.38	0.32	13.58
V	0.53	0.32	14.62
Cr	−0.28	0.33	16.49

The [M/Fe] values are calculated from [M/H] and [Fe/H] values both of which are obtained only from the singly-ionized lines.

Ⅲ-2 RV Tau

RV Tau belongs to the RVb group and the group A. According to the General Catalogue of Variable Stars (Kholopov et al. 1985)[17], the period of long-term brightness variation is 1224days. We obtained the following results for RV Tau. We obtained -0.92 and -3.07 as the $\log_{10} 2\alpha$ value from Fe I and Fe II lines, respectively. We obtained 0.31 and 0.04 as the $\Delta\theta_{I}$ and $\Delta\theta_{II}$ values, respectively, and we obtained 0.18 as the $\Delta\theta_{ion}$ value. We obtained 3.0km/s and 3.6km/s as the ξ_{mi} values from Fe I and Fe II lines, respectively.

Table 5　The relative abundance of RV Tau

The results obtained from neutral and singly－ionized line							Mean value	
Element	No.of line	$[M/H]_{I}$	Prob.Er.	No.of line	$[M/H]_{II}$	Prob.Er.	[M/H]	Prob.Er.
Fe	41	－1.30	0.10	24	－1.05	0.264	－1.27	0.06
Na	4	－0.60	0.08				－0.60	0.08
Mg	1	－1.55	0.00				－1.55	0.00
Si	6	－0.79	0.05	2	－1.22	0.021	－1.15	0.11
S	2	－0.20	0.25				－0.20	0.25
Ca	14	－1.26	0.04				－1.26	0.04
Sc	1	－1.11	0.00	8	－1.18	0.054	－1.17	0.02
Ti	8	－1.46	0.07	4	－1.11	0.148	－1.39	0.09
V	2	－1.56	0.11				－1.56	0.11
Cr	6	－1.26	0.05	8	－1.17	0.046	－1.22	0.03
Mn	3	－1.50	0.11				－1.50	0.11
Zn	2	－0.85	0.33				－0.85	0.33

$[M/H]_{I}$ and $[M/H]_{II}$ mean the [M/H] values from the neutral and singly-ionized lines, respectively, and Prob. Er. means the probable error. [M/H] means the $[M/H]_{I}$ value, when only neutral lines were measured. [M/H] means the mean value of $[M/H]_{I}$ and $[M/H]_{II}$ values calculated according to the equation (12) the probable error is calculated according to the equation (13), when both neutral and singly-ionized lines were measured.

We obtained －2.29 and －2.6 as the $[P_e]$ and [g] value, respectively. We obtained －1.27±0.06 as the relative abundance, [Fe/H].

We also obtained the relative abundance, [M/H], of 12 elements. We list the relative abundance, [M/H], of RV Tau in Table 5 together with the 50% concentration temperatures of the elements by Lodders (2003)[12].

For the elements, Si, Sc, Ti, 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 which were calculated by the equation (12). The probable errors of the relative abundances were calculated by the equation (13).

The abundance of RV Tau was obtained by Klochkova and Panchuk (1998)[14], and Giridhar et al. (2000)[18]. Klochkova and Panchuk (1998)[14] analyzed the spectra observed at the pulsational phase of 0.26 and 0.78, respectively. Klochkova and Panchuk (1998)[14] obtained 0.07 and 0.09, respectively, for the phase 0.26 and 0.78. Giridhar et al. (2000)[18] obtained －0.41 as the [Fe/H] value. The relative abundances, [M/Fe], obtained by them are listed in Table 6, together with our values. The relative abundance, [M/Fe], is calculated as the difference between [M/H] and [Fe/H].

Our values for the atmospheric parameters indicates that RV Tau 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, Giridhar et al. (2000)[18] obtained 3.0km/s and －4.4 as the ξ_{mi} value and [g] value, respectively. These values, especially, the values for the microturbulent velocity and [g], are close to our values, and it confirmes that RV Tau is a supergiant.

On the other hand, Table 6 shows that our value of [Fe/H] is markedly lower than that those obtained by the other analyses. Especially, Klochkova and Panchuk (1998)[14] obtained positive values and the difference between our value and that by them are 1.34 and 1.36, respectively, for the phase 0.26 and 0.78.

Table 6　The Comparison of the relative abundance for RV Tau

Relative abundance	G	K1	K2	M
[Fe/H]	－0.41	0.07	0.09	－1.27
[Na/Fe]				0.67
[Mg/Fe]			－0.16	－0.28
[Si/Fe]	0.11	0.06	0.08	0.12
[S/Fe]		0.82	0.82	1.07
[Ca/Fe]	－0.04	－0.11	－0.16	0.01
[Sc/Fe]	0.09	－0.26	－0.38	0.10
[Ti/Fe]	－0.09	－0.29	－0.20	－0.12
[V/Fe]		－0.11	－0.01	－0.29
[Cr/Fe]	0.16	－0.05	－0.07	0.05
[Mn/Fe]	0.04	0.34	－0.04	－0.23
[Zn/Fe]	0.42	0.09	0.09	0.42

The uppercase letters G, K1, K2, and M indicate the following capital letters of the investigators, respectively, Giridhar et al. (2000)[18], Klochkova and Panchuk (1998)[14], and this work. The [Fe/H] and [M/Fe] values for K1 are the values of Giridhar et al. (2000)[18] obtainted at the phase of 0.26 and those for K2 are the values of Giridhar et al. (2000)[18] obtainted at the phase of 0.78.

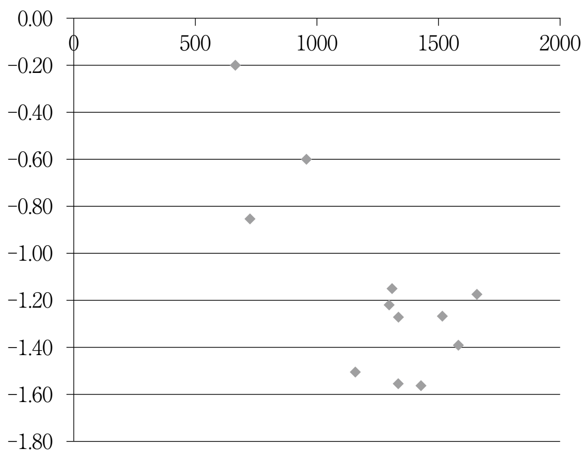

Fig. 2 The correlation between the relative abundance, [M/H], and the 50% concentration temperature, T_C, for RV Tau. The ordinate is the [M/H] value and the abscissa is the 50% concentration temperature.

This difference may be partly due to the difference in the surface temperature. Our the $\Delta\theta_I$ value is lowest among the above results. On the other hand, our values of [M/Fe] do not differ markedly from those of the other results.

Table 5 shows that there is some correlation between [M/H] and T_C, i.e., the [M/H] values decrease with the increase of the T_C values. It is also shown in Figure 2. This correlation follows the prediction by the dust-gas separation mechanism.

Table 7 shows the correlation between the [M/H] values derived from the neutral lines and the first ionization potential. As is shown in Table 7, there is not a clear correlation between the [M/H] values and the first ionization potentials. This table shows that the first ionization mechanism does not affect the photospheric abundance of RV Tau.

Table 8 shows the correlation between the [M/Fe] values derived from the singly-ionized lines and the second ionization potentials. Table 8 shows that there is not the tendency that the [M/Fe] values whose second ionization potentials are smaller than 13.60eV are smaller than the [M/Fe] values whose second ionization potentials are larger than 13.60eV. This table shows that the second ionization mechanism does not affect either the photospheric abundance of RV Tau.

Ⅳ. Discussion

According to the results in the section Ⅲ, we can conclude that the dust-gas separation mechanism is most plausible one among the three proposed mechanisms for both AC Her and RV Tau.

Table 7 The abundance of RV Tau from neutral lines.

Elemenr	[M/Fe]	Prob.Er.	The first ionization potential (eV)
[Na/Fe]	0.70	0.08	5.14
[Mg/Fe]	−0.25	0.00	7.65
[Si/Fe]	0.51	0.11	8.15
[S/Fe]	1.10	0.25	10.36
[Ca/Fe]	0.04	0.04	6.11
[Sc/Fe]	0.19	0.02	6.56
[Ti/Fe]	−0.16	0.09	6.84
[V/Fe]	−0.26	0.11	6.75
[Cr/Fe]	0.05	0.03	6.77
[Mn/Fe]	−0.20	0.11	7.43
[Zn/Fe]	0.45	0.33	9.39

The [M/Fe] values are calculated from [M/H] and [Fe/H] values both of which are obtained only from the neutral lines.

Table 8 The abundance of RV Tau from singly-ionized lines.

Element	[M/Fe]	Prob.Er.	The second ionization potential (eV)
Si	−0.17	0.26	16.35
Sc	−0.13	0.27	12.80
Ti	−0.05	0.30	13.58
Cr	−0.12	0.27	16.49

The [M/Fe] values are calculated from [M/H] and [Fe/H] values both of which are obtained only from the singly-ionized lines.

According to Giridhar et al. (2000)[18], 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 group B. They proposed that the deeper convective envelope of the group A with a cooler atmosphere dilutes anomalies resulting from dust-gas separation. However, our results indicate that the group A star, RV Tau, show a more conspicuous pattern of abundance by the dust-gas separation than the group B star, AC Her. Our desults do not confirm the results and proposition by Giridhar et al. (2000)[18], and our results suggest that there is not a clear boundary between the group A and the group B concerning the dust-gas separation.

According to Giridhar et al. (2000)[18], the post-AGB stars including the RV Tau stars with an intrinsic mtalicity $[Fe/H]_0 < -1$, 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 −1.08 and −0.53, respectively for AC Her and RV Tau. The $[Fe/H]_0$ value for AC Her is the boundary of the effectiveness of the dust-gas separation and that for RV Tau is higher than the boundary value. These values do not contradict the above result that the RV Tau shows a more conspicuous pattern of abundance by the dust-gas separation than AC Her.

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 plan to reanalyze AC Her and RV Tau by a different process of the differential curve-of-growth analysis.

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