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The Determination of Abundances of Two Stars with Planets, ε Eri and HD37124

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惑星を持つ２つの恒星、エリダヌス座ε星とHD37124の化学組成の決定

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ABSTRACT

It is known that host stars with planets have a tendency to have a large metallic abundance in their photospheres in comparison with stars without planets. One of the explanations for this tendency is the self-enrichment explanation.

We observed two stars with planets, ε Eri and HD37124, and we determined the chemical abundances of these stars in order to decide the right or wrong of the self-enrichment explanation.

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, 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/Fe] values decrease with the condensation temperature, thought the scatters are large.

2）The above correlation of the K2V star, ε Eri, is more conspicuous than that of the G4V star, HD37124.

These results are contrary to the expectations from the self-enrichment explanation. However, these results are not contrary to the expectations from other viewpoint that the fractionation of volatile and refractory elements may have occurred in the protoplanetary nebulae and significant accretion of refractory rich planet material has not taken place.

It is desired that more stars with planets are observed and more precise observations are done in order to decide the right or wrong of the self-enrichment explanation.

要　旨

惑星を持つ恒星は、惑星を持たない恒星に比べて光球中での重元素の量が多い傾向を持つことが知られている。この傾向の解釈の１つに汚染説がある。

われわれは、汚染説の成否を決定する目的で惑星を持つ２つの星、ε EriとHD37124を観測し、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った。整約はソフトアウェア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、相対成長曲線法で行った。

そして、次の結果が得られた。

１）両星とも、太陽に対する相対的な元素量と凝縮温度の関係として、データの散らばりは大きいが、[M/Fe］の値が凝縮温度とともに減少する関係が成り立つ。

２）スペクトル型がK2V型のε Eriの方が、スペクトル型がG4V型のHD37124よりも上述の傾向が顕著である。

これらの結果は、汚染説から導かれる予測に反している。しかし、原始惑星系星雲の時期に揮発性元素と不揮発性元素の分離が起こり、揮発性元素の光球への降着が起きなかったとする、別の観点からの予測には反していない。

今後は、より多くの惑星を持つ星を、より高い精度で観測して、汚染説の成否を決定することが望まれる。

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Ⅰ. Introduction

The first planetary mass object orbiting a star was discovered in 1992 by Wolszczan and Frail (1992)[1]. The host star of this object is a pulsar. The first extrasolar planet orbiting a sun-like star was discovered in 1995 by Mayor and Queloz (1995)[2]. The host star of this planet is 51 Peg with spectral type of G2.5IV or G4-5V. At the time of 2010 October, nearly 500 extrasolar planets have been discovered. Nearly all of these planet have been found with the Doppler method. Some of them have also been found with the transit and microlensing methods. Especially, the satellite, Kepler have discovered more than 2000 candidates for planet with the transit method at the time of this writing.

Gonzalez (1997)[3] first showed a link between the metallicities of stars and the presence of planets. According to him, host stars with planet have a tendence to have a large metallicity in comparison with stars without planet. For example, Luck and Heiter (2006)[4] showed that the average value of [Fe/H] for the stars with planets is larger by 0.18 in comparison with that for the stars without planets, where [Fe/H] means the logarithmic difference between the ratio of the number density of Fe to that of H for the relevant star and that of the sun, $\log_{10}(\mathrm{Fe/H})_{\mathrm{star}} - \log_{10}(\mathrm{Fe/H})_{\mathrm{the\ sun}}$. Johnson[5] showed that about the percentage of 3 out of the stars with [Fe/H] values of 0 have planets, while the percentage of more than 15 out of the stars with {Fe/H} values of more than 0.25 have planets.

There are two explanations for the above correlation between the ratio of the stars with planet to the stars without planet and the [Fe/H] values. One of them is the primordial explanation. According to this explanation, the probability of forming planets for birth clouds with large metallicity is larger than that for birth clouds with small metallicity. Consequently, the [Fe/H] of the stars with planet have the tendency to larger values. The other is the self-enrichment explanation. According to this explanation, the stars with planet suffer significant alteration of a surface chemical composition by the accretion of metal-rich planet or metal-rich planeteimal. Consequently, the [Fe/H] values of the stars with planet have inceased. According to the primordial explanation the metallicty of a parent star does not change after the formation of planet, while according to the self-enrichment explanation the metallicity changes after the formation.

It is called a hot jupiters which is orbiting parent stars with semimajor axis of less than 0.05 AU. Many hot jupiters have been found until now. According to the planet formation theory, these giant gas planet did not formed at the present orbit. They were formed outside ice lines. Then, they migrated from their birth places to the places near their parent stars due to interaction with the disc gas. Thereafter, the disc gas evaporated and these planet remained there.

If the above process occurs, there is a possibility that the giant gas planets fall into the parent stars without remaining there. If the evaporation of the disc gas or the release of the disc gas from the parent stars occurs earlier than the migration, there is a possibility that the protoplanets changes their orbits due to the gravitational interaction with other protoplanets and they fall into the parent stars. Therefore, the self-enrichment explanation seems to be highly probable.

In this study, we investigate the validity of the self-enrichment explanation by the observation of the chemical abundance of the stars with planets. We check the two correlations which are deduced from this explanation. One correlation is that between the relative abundance of an element M, [M/Fe], and the condensation temperature, T_{C}, of the element M. If the self-enrichment occurs and the accretion of material rich in refractory elements onto the parent stars occurs, the photospheres become relatively rich in refractory elements and become relatively poor in volatile elements. Therefore, the stars with planets will have the correlation of increasing [M/Fe] value with increasing T_{C} value.

The other correlation is that between the [M/Fe] value and the surface temperature. According to Pinsonneault (2001)[6], Jupiter has two earth masses of iron. If the sun accrete Jupiter, the [Fe/H] value of the sun increases by 0.09, which value is large enough to detect by observation. The mass of convective zone of the main-sequence stars with the spectral type between F type and K type decrease abruptly with surface temperature. For example, the mass of convective zone for F0 dwarf is about a tenth of that for K0 dwarf. Therefore, the dilution of accreted material by the convection zone become smaller with surface temperature. On the other hand, the mass of dwarf increases with surface temperature, so the probability of accretion for dwarfs increases with the surface temperature due to larger gravity. The effects of both the dilution and the gravity increase the contamination of chemical composition by the accretion. Therefore, the dwarf stars with planets will have the correlation of increasing the absolute value of [M/Fe] with increasing surface temperature.

We have observed the chemical abundances of two stars with planets in order to confirm the above two correlations. The first correlation is hereafter referred

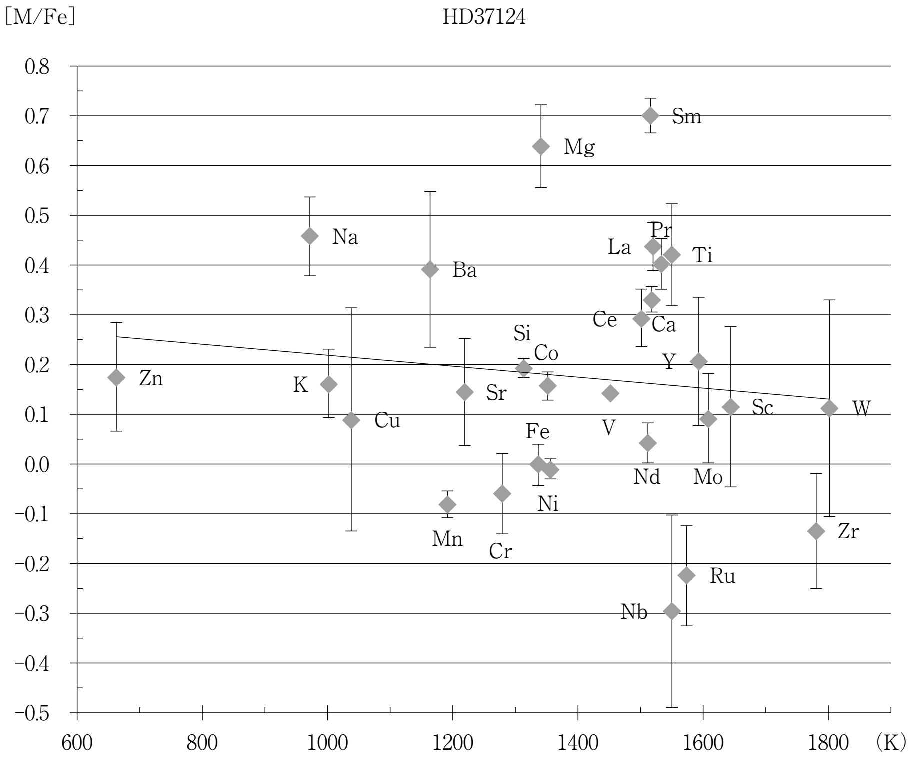

Fig. 1 The correlation between the relative abundance, [M/Fe], and the 50% condensation temperature, T_C, for HD37124. The solid line shows the least-squares solution

to as the condensation temperature correlation and the second correlation is referred to as the surface temperature correlation.

Ⅱ. Observations and Reduction

We searched the main-sequence stars which have planets and satisfy the following requirements.

1) The apparent visual magnitude is brighter than 8.5.
2) The declination is larger than 0 degree.
3) The right ascension is between 23 hours and 6 hours.

The stars which satisfy the requirements of 2) and 3) can be observed enough in Japan between September and December.

We obtained the table 1 which lists the dwarf stars with planet that satisfy the above requirements. In the search of the dwarf stars in the table 1, we used the paper by Butler[7] and the internet site by Schneider[8]. In this table, the stars with negative values of declination are added.

We have made spectroscopic observations of six stars listed in the table 1 at Gunma Astronomical Observatory (hereafter referred to as GAO) in Gunma prefecture in Japan, which are HR8799, τ Boo, HD 37124, HD12661, 14 Her, and ε Eri. The observations were made between September and December in 2010. The observations were made with the Echelle Spectrograph (hereafter referred to as GAOES) attached to the 150cm reflector at Gunma Astronomical Observatory.

Table 1 Candidate stars for observation

Star's Name	Right Ascension	Declination	Apparent visual magnitude	Spectral type
HR8799	$23^h07^m29^s$	+21° 08′ 03″	5.96	A5V
τ Boo	$13^h47^m17^s$	+17° 27′ 22″	4.50	F7V
HD11506	$01^h52^m51^s$	−19° 30′ 25″	7.51	G0V
HD37124	$05^h37^m02^s$	+20° 43′ 50″	7.68	G4V
HD49674	$06^h51^m30^s$	+40° 52′ 03″	8.10	G5V
HD12661	$02^h04^m34^s$	+25° 24′ 51″	7.44	G6V
14 Her	$16^h10^m23^s$	+43° 49′ 18″	6.67	K0V
ε Eri	$03^h32^m55^s$	−09° 27′ 29″	3.73	K2V

We have analyzed two stars, HD37124 and ε Eri out of the above six stars. The spectral types of HD37124 and ε Eri are G4V and K2V, respectively. The spectral resolution was about 60000 and S/N ratio was about 100. The observations were made with a spectral coverage from 453 nm to 640 nm. 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. We analyzed the spectrums of HD37124 and ε Eri which were observed on the 7th of October in 2010 and on 21th of September in 2010, respectively.

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 lists by Thevenin (1989)[9] and Thevenin (1990)[10]. The line list of the solar spectrum by Moore et al. (1966)[11] 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 $\log_{10}gf\lambda + \theta_{ex} \cdot \Delta\chi$ 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 $\log_{10}(Wc/2R_C V_D \lambda)$ 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)[12] was used. The program made by Yoshioka (1987)[13] 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, $\log_{10}2\alpha$, 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, $\log_{10}Q_{\mathrm{star}} - \log_{10}Q_{\mathrm{the\ sun}}$.

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

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.

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

where $\Delta\theta_{\mathrm{I}}$ and $\Delta\theta_{\mathrm{II}}$ 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)[14]. The microturbulence velocity, ξ_{mi}, is calculated by the following equation,

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

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

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

The V_D value is calculated by the following equation,

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

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

Table 2 The relative abundance, [M/Fe], of HD37124 and the 50% condensation temperature, T_C. The [Fe/H] value is equal to −0.51±0.04 (p.e). The T_C value of Fe is equal to 1336K

Element	[M/Fe]	p.e.	T_C (K)	Element	[M/Fe]	p.e.	T_C (K)
Zn	0.18	0.11	640	Nd	0.05	0.04	1510
Na	0.46	0.08	970	Sm	0.70	0.04	1515
K	0.16	0.07	1000	Ca	0.33	0.03	1518
Cu	0.09	0.23	1037	La	0.44	0.05	1520
Ba	0.39	0.16	1162	Pr	0.41	0.05	1532
Mn	−0.08	0.03	1190	Ti	−0.09	0.10	1549
Sr	0.15	0.11	1217	Nb	−0.29	0.19	1550
Cr	−0.06	0.08	1277	Ru	−0.22	0.10	1573
Si	0.20	0.02	1311	Y	0.21	0.13	1592
Mg	0.64	0.08	1340	Mo	0.09	0.09	1608
Co	0.16	0.03	1351	Sc	−0.39	0.16	1644
Ni	−0.01	0.02	1354	Zr	0.12	0.12	1780
V	0.14	0.14	1450	W	0.11	0.22	1802
Ce	0.30	0.06	1500				

account.

The relative abundance of the element M, [M/H], is calculated from

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

for neutral lines, and

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

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,

$$\log_{10} P_{\mathrm{e}} = 0.45 + [P_{\mathrm{e}}]. \qquad (9)$$

In the above equation, the $\log_{10} P_{\mathrm{e}}$ value of the Sun is taken to be 0.45 after Cayrel and Jugaku (1963)[14]. 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,

$$[g] = [P_{\mathrm{H}}] + [P_{\mathrm{e}}] + 1.9\cdot(\Delta\theta_{\mathrm{I}} + \Delta\theta_{\mathrm{II}})/2 - [\tau] + [3X+1], \qquad (6)$$

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)[15]. 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 $[P_{\mathrm{H}}]$ value is calculated from the ionization equation

$$[P_{\mathrm{H}}] = [P_{\mathrm{e}}] - [x_{\mathrm{H}} + (\mathrm{Mg/H})_{\mathrm{S}} 10^{[\mathrm{Mg/H}]} x_{\mathrm{Mg}} + (\mathrm{Si/H})_{\mathrm{S}} 10^{[\mathrm{Si/H}]} x_{\mathrm{Si}} + (\mathrm{Fe/H})_{\mathrm{S}} 10^{[\mathrm{Fe/H}]} x_{\mathrm{Fe}}, \qquad (10)$$

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 HD37124 and ε Eri

We obtained the equivalent widths for HD37124 and ε Eri from the plate listed in table 2, using the IRAF image processing software. We used the values listed in the table by Moore et al. (1966)[11] 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)[16] 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 the identification of absorption lines.

Ⅲ-1 HD37124

We obtained the following results for HD37124. We obtained −1.01 and −1.84 as the $\log_{10}2\alpha$ value from Fe Ⅰ and Fe Ⅱ lines, respectively. We obtained 0.09 and −0.13 as the $\Delta\theta_{\mathrm{I}}$ and $\Delta\theta_{\mathrm{II}}$ values and we obtained −0.02 as the $\Delta\theta_{\mathrm{ion}}$ value. We obtained 0.5km/s and 1.3km/s as the ξ_{mi} values from Fe Ⅰ and Fe Ⅱ lines, respectively. We obtained 0.33 as the $[P_{\mathrm{e}}]$ value.

We obtained the relative abundance, [M/Fe], of 28 elements. We list the relative abundance of HD37124 in table 2 together with the 50% concentration temperatures of the elements. The [M/Fe] value was calculated as the difference between the [M/H] value

Table 3 The relative abundance, [M/Fe], of εEri and the 50% condensation temperature, T_C. The [Fe/H] value is equal to 0.06 ± 0.04 (p.e). The T_C value of Fe is equal to 1336K

Element	[M/Fe]	p.e.	T_C (K)	Element	[M/Fe]	p.e.	T_C (K)
Zn	0.40	0.12	640	Nd	−0.67	0.04	1510
Na	0.17	0.09	970	Sm	−0.66	0.05	1515
K	−0.45	0.04	1000	Ca	0.05	0.03	1518
Cu	0.04	0.26	1037	La	−0.60	0.06	1520
Ba	−1.04	0.29	1162	Pr	−0.73	0.10	1532
Mn	−0.00	0.02	1190	Ti	−0.23	0.17	1549
Sr	0.18	0.06	1217	Nb	−0.06	0.31	1550
Cr	0.11	0.21	1277	Ru	0.11	0.06	1573
Si	0.17	0.02	1311	Y	−0.45	0.03	1592
Mg	0.37	0.08	1340	Mo	0.19	0.10	1608
Co	0.50	0.03	1351	Sc	−0.36	0.11	1644
Ni	−0.09	0.02	1354	Zr	−0.05	0.09	1780
V	−0.14	0.02	1450	W	0.08	0.30	1802
Ce	−0.56	0.04	1500				

and the [Fe/H] value. The 50% concentration temperature were taken from the table by Lodders (2003)[17]. Lodders (2003)[17] calculated the 50% condensation temperatures assuming a solar-system composition gas and a total pressure of 10^{-4} bar.

For the elements, Sc, Ti, V, Cr, Fe, Y, and Zr, 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 ;

$$[M/H]=([M/H]_{I}/pe_{I}^{2}+[M/H]_{II}/pe_{II}^{2})/(1/pe_{I}^{2}+1//pe_{II}^{2}), \qquad (11)$$

and the probable error, pe, was calculated by the follow ing equation ;

$$pe=0.6745\times\{([M/H]_{I}-[M/H])^{2}/pe_{I}^{2}+([M/H]_{II}-[M/H])^{2}/pe_{II}^{2}\}/(1/pe_{I}^{2}+1//pe_{II}^{2}). \qquad (12)$$

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.

Ⅲ-2 ε Eri

We obtained the following results for ε Eri. We obtained −0.82 and −0.87 as the $\log_{10}2\alpha$ value from FeⅠ and FeⅡ lines, respectively. We obtained 0.09 and 0.51 as the $\Delta\theta_{I}$ and $\Delta\theta_{II}$ values and we obtained 0.30 as the $\Delta\theta_{ion}$ value. We obtained 1.4km/s and 1.1km/s as the ξ_{mi} values from FeⅠ and FeⅡ lines, respectively. We obtained −1.62 as the $[P_e]$ value.

We obtained the relative abundance of 28 elements. We list the relative abundance, [M/Fe], of ε Eri in table 3 together with the 50% concentration temperatures of the elements.

For the elements, Sc, Ti, V, Cr, Fe, Y, and Zr, both neutral and singly-ionized lines were used to obtain the relative abundances. The relative abundances, [M/Fe], for these elements are the weighted means of values from neutral and singly-ionized lines.

Ⅳ. Duscussion

According to the description in the section Ⅱ, we expected the following two results.

1) There is the correlation between the relative abundance and the condensation temperature for both of the stars that the [M/Fe] values increase with the condensation temperature.
2) The above correlation of the G4V star, HD37124, is more conspicuous than that of the K2V star, ε Eri.

Figure 1 shows the correlation between the relative abundance, [M/Fe], and the 50% concentration temperature, T_C, for HD37124. The straight line shows the least squares solution of the above correlation.

As is shown in this figure, the expected correlation does not hold for HD37124. The opposite correlation rather holds, though the scatter around the straight line is large. The [Fe/H] value of −.51 also is contrary to the expected value, because, according to the self-enrichment explanation, the [Fe/H] value is epected to be positive value.

Figure 2 shows the correlation between the relative abundance and the 50% concentration temperature for ε Eri. The straight line shows the least squares solution of the above correlation.

As is shown in this figure, the expected correlation does not holds either for ε Eri. The opposite correla-

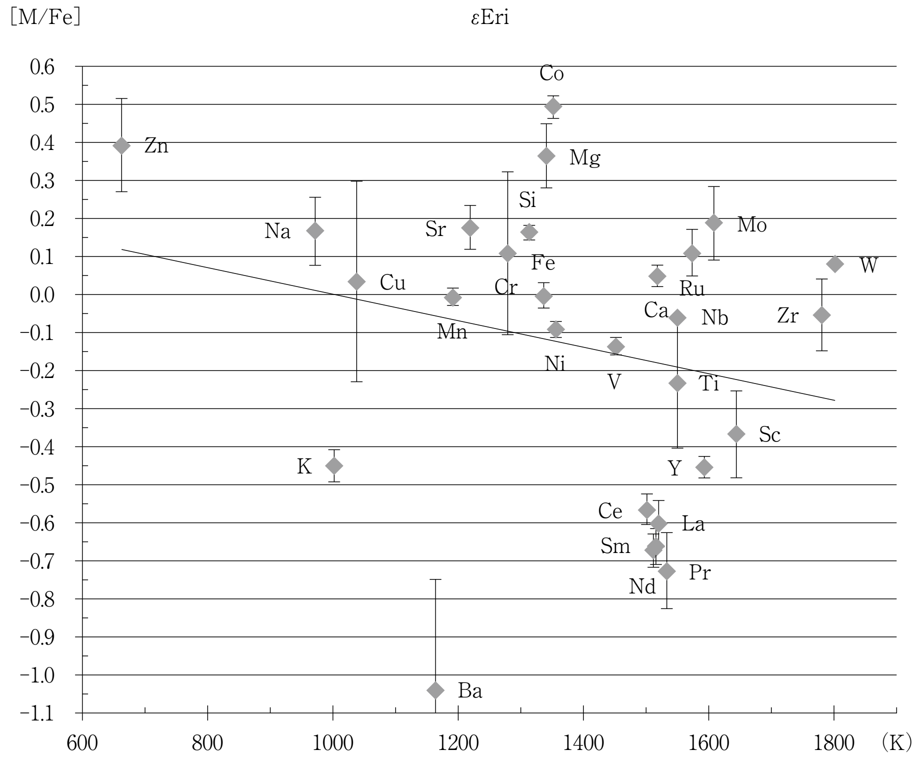

Fig. 2 The correlation between the relative abundance, [M/Fe], and the 50% condensation temperature, T_{C}, for ε Eri. The solid line shows the least-squares solution

tion also holds, though the scatter around the straight line is large. However, the [Fe/H] value of 0.06 is not contrary to the expected value.

Figure 3 shows the correlation between the differences, [M/Fe]$_{\mathrm{HD37124}}$ − [M/Fe]$_{\varepsilon\,\mathrm{Eri}}$, and the 50% condensation temperature, where [M/Fe]$_{\mathrm{HD37124}}$ and [M/Fe]$_{\varepsilon\mathrm{Eri}}$ mean the [M/Fe] value for HD37124 and ε Eri, respectively. The straight line shows the least squares solution. According to the expectation 2), the differences should decrease with the 50% condensation temperature. Figure 3 indicates the expected correlation does not holds and the opposite correlation holds, though the scatter around the straight line is very large.

As is above described, out results do not support the self-enrichment explanation. However, our results do not deny completely the self-enrichment explanation.

Schuler et al. (2011)[18] indicated that the sun is depleted in refractory elements relative to volative elements when compared to the stars which resemble the sun and have not planets. According to them, the abundances of the sun relative to the stars without planets decrease with increasing T_{C}. They interpret that the above trend is a possible signature of terrestrial planet formation in the solar system, suggesting that the refractory elements depleted in the solar photosphere are locked up in the terrestrial planets. Moreover, they made the precise determination of abundance of 18 elements for 10 stars known to host giant planets. When considering the refractory elements ($T_{\mathrm{C}} \geqq 900$K) only, which may be more sensitive to planet formation process, the above 10 stars are separated into two groups. The four stars form one group, where the stars have positive slope for the relation between the [M/Fe] values and the T_{C} values, i.e., the [M/Fe] values increase with increasing T_{C} values. On the other hand, the six stars form another group, where the stars have flat or negative slopes, i.e., the [M/Fe] values are constant or decrease with increasing T_{C} values. The stars of the former group have very close-in giant planets. They suggest that the stars of the former group have accreted refractory-rich planet material and that the fractionation of volatile and refractory elements may have occurred in the proto-planetary nebulae for the latter group and significant accretion of refractory-rich planet material has not taken place despite having a giant planet on a close-in orbit. According to their suggestion, the flat or negative slopes indicate the formation of both the giant and terrestrial planets.

HD37124 has three giant planets with about 0.6 jovian mass. The semi-major radius of most inner planet is equal to 0.5AU. On the other hand, ε Eri has a giant planet with 1.5 jovian mass. This star may have another planet. Recently, two asteroid belts near ε Eri

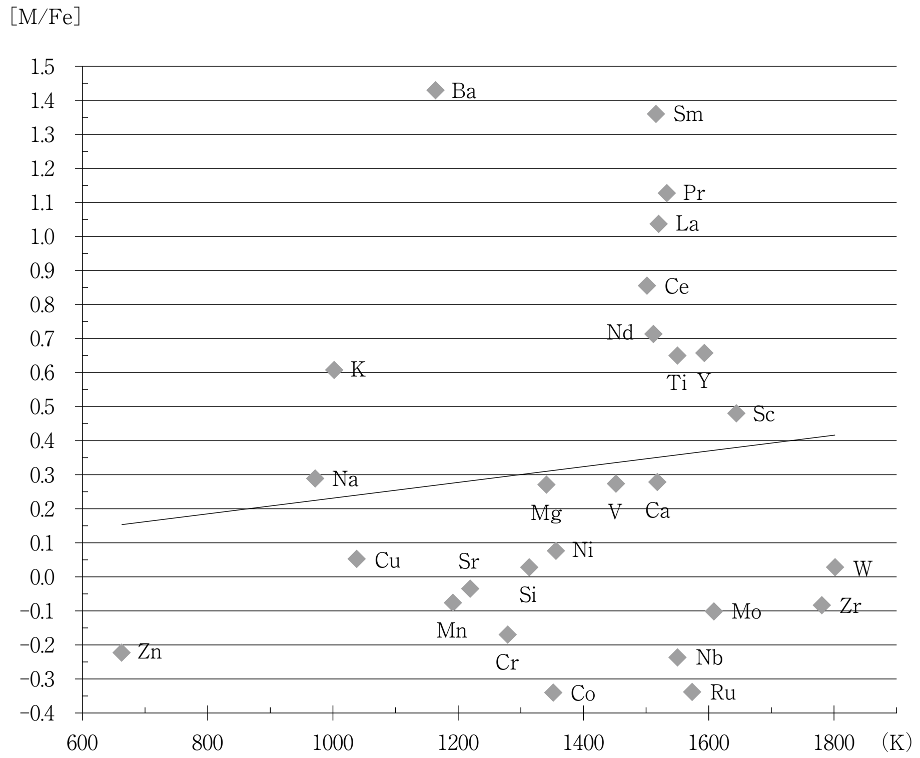

Fig. 3 The correlation between the relative abundance, $[M/Fe]_{HD37124} - [M/Fe]_{\varepsilon Eri}$, and the 50% condensation temperature. The solid line shows the least-squares solution

were detected by the observation of Spitzer Space Telescope (Clavin 2008)[19]. The above observations for HD37124 and ε Eri suggest that both of the stars have terrestrial plantes. If this is true, the results obtained by us does not contradict the self-enrichment explanation.

Our observation does not decide the right or wrong of the self-enrichment explanation. It is desired that more stars with planets are observed and more precise observations are done in order to decide the right or wrong of the self-enrichment explanation. Concerning the latter desire, the data of our observation are being checked and the analysis will be done anew with the checked data.

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