A&A 581, L2 (2015)
DOI: 10.1051/0004-6361/201527059

Astronomy & Astrophysics

Letter to the Editor

From stellar to planetary composition: Galactic chemical evolution of Mg/Si mineralogical ratio

V. Adibekyan[1], N. C. Santos[1,2], P. Figueira[1], C. Dorn[3], S. G. Sousa[1], E. Delgado-Mena[1], G. Israelian[4,5], A. A. Hakobyan[6], and C. Mordasini[3]

[1] Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal
e-mail: Vardan.Adibekyan@astro.up.pt
[2] Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Rua do Campo Alegre, 4169-007 Porto, Portugal
[3] Physikalisches Institut, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
[4] Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain
[5] Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain
[6] Byurakan Astrophysical Observatory, 0213 Byurakan, Aragatsotn province, Armenia

Received 25 July 2015 / Accepted 19 August 2015

ABSTRACT

Aims. The main goal of this work is to study element ratios that are important for the formation of planets of different masses.

Methods. We study potential correlations between the existence of planetary companions and the relative elemental abundances of their host stars. We use a large sample of FGK-type dwarf stars for which precise Mg, Si, and Fe abundances have been derived using HARPS high-resolution and high-quality data.

Results. A first analysis of the data suggests that low-mass planet host stars show higher [Mg/Si] ratios, while giant planet hosts present [Mg/Si] that is lower than field stars. However, we found that the [Mg/Si] ratio significantly depends on metallicity through Galactic chemical evolution. After removing the Galactic evolution trend only the difference in the [Mg/Si] elemental ratio between low-mass planet hosts and non-hosts was present in a significant way. These results suggest that low-mass planets are more prevalent around stars with high [Mg/Si].

Conclusions. Our results demonstrate the importance of Galactic chemical evolution and indicate that it may play an important role in the planetary internal structure and composition. The results also show that abundance ratios may be a very relevant issue for our understanding of planet formation and evolution.

Key words. planetary systems – techniques: spectroscopic – stars: abundances – planets and satellites: composition – Galaxy: abundances

1. Introduction

It is well known that stellar metallicity is a key parameter for the formation and evolution of planets. In particular, it has been shown that giant planet formation is more efficient around metal-rich stars (e.g. Gonzalez 1997; Santos et al. 2004; Johnson et al. 2010; Mortier et al. 2013), while this planet–metallicity correlation probably does not hold for lower-mass/small-size planets (e.g. Sousa et al. 2011b; Mayor et al. 2011; Buchhave et al. 2012). It has also been recently shown that stellar metallicity plays an important role in the architecture of planetary orbits (e.g. Dawson & Murray-Clay 2013; Beaugé & Nesvorný 2013; Adibekyan et al. 2013b).

In all of the works cited, the iron content was used as a proxy for the overall metallicity. Building on this, many authors searched for chemical peculiarities of planet hosting stars in terms of abundances of individual elements. While many contradictory results were obtained (e.g. Santos et al. 2000; Bodaghee et al. 2003; Bond et al. 2006; Robinson et al. 2006; Kang et al. 2011; Brugamyer et al. 2011), the enhancement of α-elements of iron-poor planet hosts was shown to be robust (Haywood 2008; Adibekyan et al. 2012a,b). Interestingly, Adibekyan et al. (2012a) showed that low-mass/small-size planets show α-enhancement at iron-poor regimes. This result suggests that although low-mass/small-size planets can be formed at a wide range of metallicities (Buchhave et al. 2012; Mordasini et al. 2012), extra heavy elements are required to "compensate" for the lack of iron in low-metallicity environments.

Interestingly, observational and theoretical studies suggest that abundances ratios of individual elements in a circumstellar disk determine the structure and composition of the planets that are formed (e.g. Grasset et al. 2009; Bond et al. 2010; Delgado Mena et al. 2010; Rogers & Seager 2010; Thiabaud et al. 2014, 2015; Dorn et al. 2015). Among the most important mineralogical ratios are the Mg/Si, Fe/Si, and C/O ratios that can be used to constrain the chemical composition of terrestrial planets (e.g. Bond et al. 2010; Thiabaud et al. 2015; Dorn et al. 2015). Recently, Dressing et al. (2015) showed that all the terrestrial planets in their sample with masses lower than 6 $M_{\oplus}$ lie in the same mass-radius area as Earth and Venus. Their suggestion that these planets can be explained by Earth-like composition was successfully tested by Santos et al. (2015). The authors derived iron mass fractions of the planets using chemical abundance proxies of their host stars and found that it varies from 27.5 to 34.7 %, being similar with the iron mass fraction for the Earth (29−32% e.g. McDonough & Sun 1995).

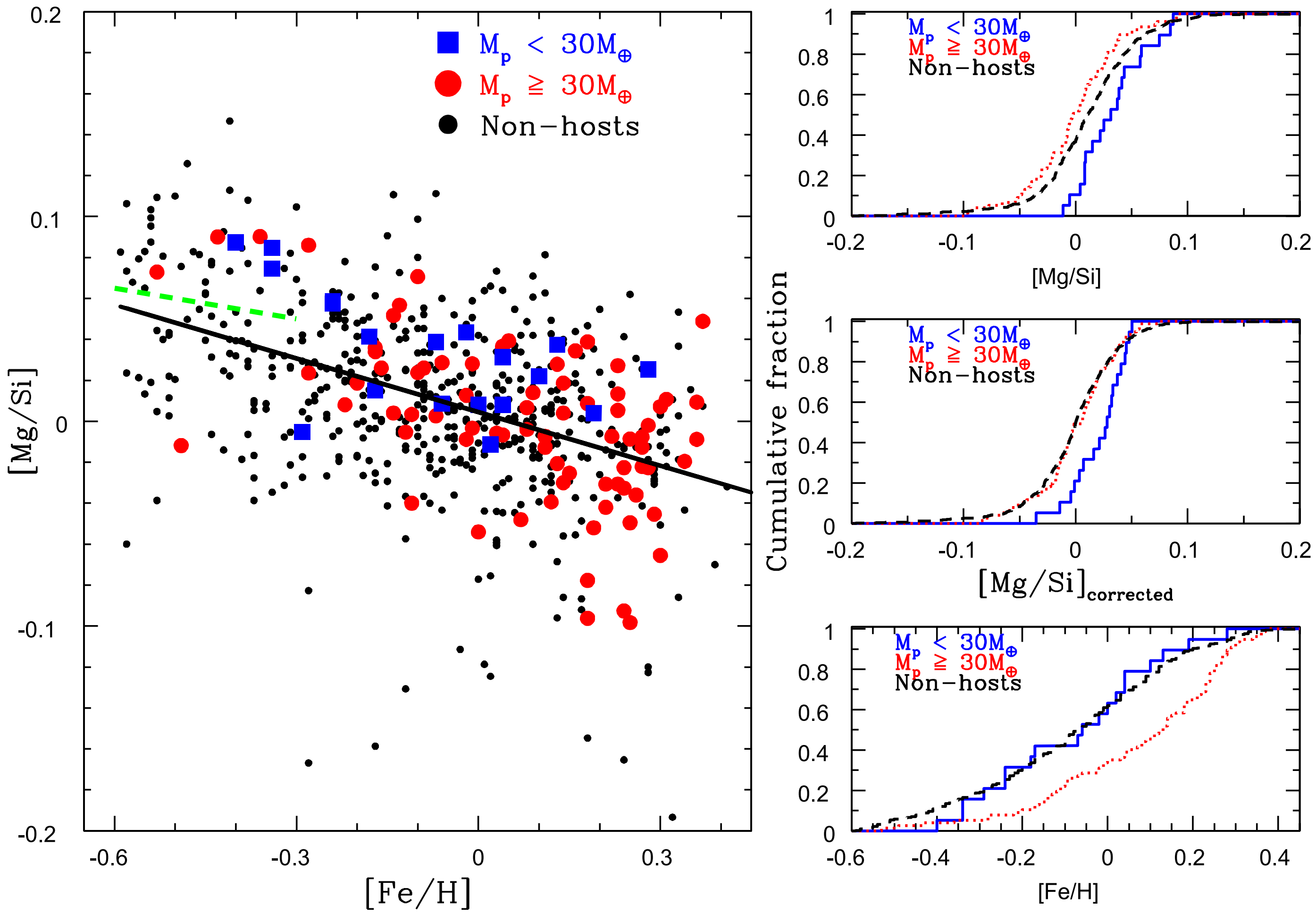

Fig. 1. *Left*: [Mg/Si] versus [Fe/H] for stars without detected planets (black dots), stars hosting low-mass planets (blue squares), and stars hosting high-mass planets (red filled circles). Cumulative distribution of [Mg/Si] (*top right*), [Mg/Si] after correcting for the Galactic chemical evolution (*middle right*), and [Fe/H] (*bottom right*) for stars with and without detected planets. The black solid line provides linear fit to all the data points and the green dashed line shows separation between Galactic thin- and thick-disk stars.

Motivated by these recent works, we decided to explore these important elemental ratios in stars harbouring different type of planets. The main goal of this work is to verify whether planet hosts exhibit peculiar elemental ratios of Mg/Si and to understand the origin of possible peculiarities. We organized this Letter as follows. In Sect. 2 we present the sample; in Sect. 3 we present and discuss the results. We finish the paper with concluding remarks in Sect. 4.

2. The sample

Our initial sample consists of 1111 FGK-type stars with and without detected planets that were observed with the HARPS spectrograph (Adibekyan et al. 2012c). This work provides precise chemical abundances of 12 refractory elements derived in a homogeneous manner. The stellar atmospheric parameters of the stars were taken from Sousa et al. (2008, 2011b,a).

To study stars with the most precise stellar parameters and chemical abundances we selected only dwarf ($\log g \geq 4$) stars with effective temperatures within 500 K from that of the Sun ($T_{\odot}$ = 5777 K; see the discussion in Adibekyan et al. 2012c; Tsantaki et al. 2013, for details). We also constrained our sample by selecting stars for which errors on Mg, Si, and Fe abundances are smaller than 0.2 dex. We note that this value is very conservative and guarantees exclusion of any possible outliers for which very precise abundances could not be derived (due to e.g. cosmic rays around some spectral lines or low signal-to-noise ratio in the spectra). We also note that our results are not sensitive to this constraint on precision and all the conclusions remain the same. Finally, we only selected stars that have metallicity higher than −0.6 dex which is the lower [Fe/H] limit of planet hosting stars in the sample.

Our final sample consists of 493 stars without detected planetary companions, 19 stars hosting super-Earths or Neptune-like planets (the most massive planet in the system has $M_p < 30\ M_{\oplus}$) and 77 Jovian hosts ($M_p \geq 30\ M_{\oplus}$).

3. Results and discussion

Since Adibekyan et al. (2012a,c) already discussed the possible differences in individual elemental abundances and [X/Fe] abundances ratios between stars without detected planets and stars hosting low-mass and high-mass planets, in this work we focus on the [Mg/Si] ratio. We remind the reader that Adibekyan et al. (2012a) showed that stars hosting planets show enhancement in α-elements (high [Si/Fe] and [Mg/Fe] ratios) relative to non-hosts at low-iron regime.

In the left panel of Fig. 1, we plot the dependence of the [Mg/Si] ratio on stellar metallicity for stars with and without detected planets. The top right panel shows the cumulative

Table 1. KS and AD probabilities that planet hosts and stars without detected planets come from the same parent distribution.

		[Mg/Si]	$[Mg/Si]_{corr}$	[Fe/H]
P_{KS}	Neptune – Non-host	0.037	0.009	0.973
	Jovian – Non-host	0.051	0.736	1.2×10^{-6}
P_{AD}	Neptune – Non-host	0.020	0.003	0.883
	Jovian – Non-host	0.017	0.841	8.6×10^{-6}

distributions of [Mg/Si] ratios for the three groups of stars. As can be easily seen, the [Mg/Si] distributions differ among the groups: Low-mass planet hosts have higher [Mg/Si] and high-mass planet hosts have lower [Mg/Si] ratios than their non-host counterparts. To quantify these differences we applied the two-sample Kolmogorov-Smirnov (KS) and the Anderson-Darling (AD)[1] tests. Both KS and AD statistics yield a low probability that low-mass and high-mass planet hosts come from the same [Mg/Si] distribution as the non-host stars (see Table 1).

The left plot, however, clearly shows that the [Mg/Si] ratio depends on metallicity[2]. Taking also into account the fact that stars hosting high-mass planets show a metallicity distribution different from that of "single" stars (see the last column of Table 1), one can argue that this metallicity difference can be responsible for the difference in [Mg/Si] distribution between Jovian hosts and non-hosts. To remove the trend of [Mg/Si] with Galactic chemical evolution (GCE) we fitted all our data points (all stars with and without detected planets) with a linear dependence on metallicity and then subtracted the fit. To the subtracted data we applied the KS and AD tests again, and found that the difference in [Mg/Si] between Jovian hosts and the single stars disappears, suggesting that the [Mg/Si] difference in the original dataset was just a reflection of GCE and the shift of giant-planet hosts towards high metallicities.

The difference in [Mg/Si] after correction for the GCE ($[Mg/Si]_{corr}$) between Neptune hosts and non-hosts remains, and the applied statistical tests predict even lower probabilities that the two samples come from the same parent distribution. To evaluate the statistical significance of the observed difference in $[Mg/Si]_{corr}$, we performed two simple Monte Carlo (MC) tests. In the first test, we randomly draw 19 stars (this is the total number of low-mass planet hosts) from the non-host sample and applied the KS test on the distributions. We repeated the entire process 10^5 times and counted the number of trials in which the P_{KS} is equal to or smaller than 0.009 (the probability that Neptunian hosts and non-hosts come from the same $[Mg/Si]_{corr}$ distribution; see Table 1). Only in 0.5% of the cases did we obtain a $P_{KS} \leq 0.009$, which means that the observed difference is most likely not obtained by chance.

We performed a second MC test in which we counted the number of low-mass planet hosts that lie above the linear fit of the GCE (15 out of 19), and again 10^5 times randomly drew 19 stars from the non-host sample every time counting the number of trials in which at least 15 stars lie above this line. The test again showed that the probability of obtaining the observed $[Mg/Si]_{corr}$ distribution by chance is very low, i.e. 0.9%.

A word of caution should be added at this point. The abundances of both Mg and Si are derived by assuming local thermodynamic equilibrium (LTE). The non-LTE effects depend on the stellar parameters of the stars. Hence, if the samples of the Neptunian hosts and stars without detected planets have significantly different distribution of stellar parameters, then the obtained difference in the [Mg/Si] ratio might be affected. Several works in the literature have already tried to quantify the non-LTE effects in Mg and Si, and their dependence on the stellar parameters (e.g. Zhao & Gehren 2000; Shi et al. 2011; Merle et al. 2011; Sukhorukov & Shchukina 2012; Bergemann et al. 2013). These works show that the non-LTE effects are usually stronger, being non-negligible for evolved, hot, and metal-poor stars. As mentioned in Sect. 2, the stars in this work were selected specifically to be main sequence (dwarfs), and to have temperatures similar to that of the Sun. When comparing the atmospheric parameters of the two samples we found that the hosts of low-mass planets are slightly cooler ($\Delta T_{eff} = (5645 \pm 196)_{Neptune} - (5771 \pm 247)_{non-host} = -126$ K) than their counterparts without planets, but have similar metallicities (Δ[Fe/H] $= (-0.08 \pm 0.19)_{Neptune} - (-0.08 \pm 0.23)_{non-host} = 0.0$ dex) and are at the same evolutionary stage ($\Delta \log g = (4.38 \pm 0.07)_{Neptune} - (4.41 \pm 0.12)_{non-host} = -0.03$ dex). The results of the aforementioned references leads us to conclude that this small difference of 100 K (which is within the dispersion of the T_{eff} values of each sub-sample) in temperature is not expected to be responsible for the significant difference observed in [Mg/Si] between Neptunian hosts and non-hosts. However, only the non-LTE corrections of the Mg and Si abundances would provide precise quantification of the impact of this difference in T_{eff} on the [Mg/Si] ratio.

4. Concluding remarks

The dependence of [Mg/Si] on metallicity, i.e. the Galactic evolution of [Mg/Si] ratio, may play an important role in the internal structure and composition of terrestrial planets. Because they are α-capture elements, Mg and Si are mostly products of massive stars. The main mechanisms for the production of Mg are C and Ne burning, while for Si, it is explosive and non-explosive O burning (e.g. Woosley & Weaver 1995; Thielemann et al. 1996). While Mg (like O) is almost exclusively produced in massive stars, the production of Si by Supernovae type Ia is not negligible. This difference in the production sites is reflected in the trends observed in the [Mg/Fe] and [Si/Fe] versus [Fe/H] plots (e.g. Fulbright et al. 2007; Adibekyan et al. 2012c).

We find that low-mass planets are more prevalent around stars with high [Mg/Si] and that the [Mg/Si] ratio depends on stellar metallicity may have important implications. The first finding is that Mg/Si ratio probably plays a very important role in the formation of these low-mass planets. The second result is that there is probably a dependence of the planetary structure on the Galactic evolution i.e. low-mass planets that were formed at different times and at different places in the Galaxy may tend to have different structures and compositions. In particular, the left panel of Fig. 1 shows that stars belonging to the Galactic thick disk (the stars above the green dashed line) have higher [Mg/Si] ratio than their thin disk counterparts (below the line)[3]. Taking into account the fact that planet-hosting stars at low metallicities mostly belong to the Galactic thick disk (Haywood 2008; Adibekyan et al. 2012b) one can speculate that the oldest terrestrial planetary systems (e.g. Kepler-444; Campante et al. 2015) may have different compositions to the terrestrial solar system planets; however, for the exact derivation of the chemical properties of these planets precise abundances of C and O are

[1] AD is similar to the KS test, but more sensitive (gives more weight) to the tails of distribution.

[2] The performed liner fit suggests that [Mg/Si] = 0.0045(±0.0017) – 0.0873(±0.0071)×[Fe/H].

[3] The separation of the thin and thick disk stars is described in Adibekyan et al. (2011, 2013a).

also needed[4]. While we already derived oxygen abundance for most of the stars in this sample (Bertran de Lis et al. 2015) the derivation of carbon abundances is still in progress (Suárez-Andrés et al., in prep.; Delgado Mean et al., in prep.).

Summarizing our results, we can conclude that stars formed at different times and places in the Galaxy have a different probability of forming low-mass planets, and the composition of the formed planets will also depend on the chemical composition of the environment in which they formed.

Acknowledgements. This work was supported by Fundação para a Ciência e a Tecnologia (FCT) through the research grant UID/FIS/04434/2013. P.F., N.C.S., and S.G.S. also acknowledge the support from FCT through Investigador FCT contracts of reference IF/01037/2013, IF/00169/2012, and IF/00028/2014, respectively, and POPH/FSE (EC) by FEDER funding through the program "Programa Operacional de Factores de Competitividade – COMPETE". P.F. further acknowledges support from Fundação para a Ciência e a Tecnologia (FCT) in the form of an exploratory project of reference IF/01037/2013CP1191/CT0001. V.A. and E.D.M. acknowledge the support from the Fundação para a Ciência e Tecnologia, FCT (Portugal) in the form of the grants SFRH/BPD/70574/2010 and SFRH/BPD/76606/2011, respectively. G.I. acknowledges financial support from the Spanish Ministry project MINECO AYA2011-29060. This work results within the collaboration of the COST Action TD 1308.

References

Adibekyan, V. Z., Santos, N. C., Sousa, S. G., & Israelian, G. 2011, A&A, 535, L11
Adibekyan, V. Z., Delgado Mena, E., Sousa, S. G., et al. 2012a, A&A, 547, A36
Adibekyan, V. Z., Santos, N. C., Sousa, S. G., et al. 2012b, A&A, 543, A89
Adibekyan, V. Z., Sousa, S. G., Santos, N. C., et al. 2012c, A&A, 545, A32
Adibekyan, V. Z., Figueira, P., Santos, N. C., et al. 2013a, A&A, 554, A44
Adibekyan, V. Z., Figueira, P., Santos, N. C., et al. 2013b, A&A, 560, A51
Beaugé, C., & Nesvorný, D. 2013, ApJ, 763, 12
Bergemann, M., Kudritzki, R.-P., Würl, M., et al. 2013, ApJ, 764, 115
Bertran de Lis, S., Delgado Mena, E., Adibekyan, V. Z., Santos, N. C., & Sousa, S. G. 2015, A&A, 576, A89
Bodaghee, A., Santos, N. C., Israelian, G., & Mayor, M. 2003, A&A, 404, 715
Bond, J. C., Tinney, C. G., Butler, R. P., et al. 2006, MNRAS, 370, 163
Bond, J. C., O'Brien, D. P., & Lauretta, D. S. 2010, ApJ, 715, 1050
Brugamyer, E., Dodson-Robinson, S. E., Cochran, W. D., & Sneden, C. 2011, ApJ, 738, 97
Buchhave, L. A., Latham, D. W., Johansen, A., et al. 2012, Nature, 486, 375
Campante, T. L., Barclay, T., Swift, J. J., et al. 2015, ApJ, 799, 170
Dawson, R. I., & Murray-Clay, R. A. 2013, ApJ, 767, L24
Delgado Mena, E., Israelian, G., González Hernández, J. I., et al. 2010, ApJ, 725, 2349
Dorn, C., Khan, A., Heng, K., et al. 2015, A&A, 577, A83
Dressing, C. D., Charbonneau, D., Dumusque, X., et al. 2015, ApJ, 800, 135
Fulbright, J. P., McWilliam, A., & Rich, R. M. 2007, ApJ, 661, 1152
Gonzalez, G. 1997, MNRAS, 285, 403
Grasset, O., Schneider, J., & Sotin, C. 2009, ApJ, 693, 722
Haywood, M. 2008, A&A, 482, 673
Johnson, J. A., Aller, K. M., Howard, A. W., & Crepp, J. R. 2010, PASP, 122, 905
Kang, W., Lee, S.-G., & Kim, K.-M. 2011, ApJ, 736, 87
Mayor, M., Marmier, M., Lovis, C., et al. 2011, A&A, submitted [arXiv:1109.2497]
McDonough, W., & Sun, S. 1995, Chemical Geology, 120, 223
Merle, T., Thévenin, F., Pichon, B., & Bigot, L. 2011, MNRAS, 418, 863
Mordasini, C., Alibert, Y., Benz, W., Klahr, H., & Henning, T. 2012, A&A, 541, A97
Mortier, A., Santos, N. C., Sousa, S., et al. 2013, A&A, 551, A112
Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, ApJ, 743, L16
Robinson, S. E., Laughlin, G., Bodenheimer, P., & Fischer, D. 2006, ApJ, 643, 484
Rogers, L. A., & Seager, S. 2010, ApJ, 712, 974
Santos, N. C., Israelian, G., & Mayor, M. 2000, A&A, 363, 228
Santos, N. C., Israelian, G., & Mayor, M. 2004, A&A, 415, 1153
Santos, N. C., Adibekyan, V., Mordasini, C., et al. 2015, A&A, 580, L13
Shi, J. R., Gehren, T., & Zhao, G. 2011, A&A, 534, A103
Sousa, S. G., Santos, N. C., Mayor, M., et al. 2008, A&A, 487, 373
Sousa, S. G., Santos, N. C., Israelian, G., et al. 2011a, A&A, 526, A99
Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Udry, S. 2011b, A&A, 533, A141
Sukhorukov, A. V., & Shchukina, N. G. 2012, Kinematics and Physics of Celestial Bodies, 28, 169
Thiabaud, A., Marboeuf, U., Alibert, Y., et al. 2014, A&A, 562, A27
Thiabaud, A., Marboeuf, U., Alibert, Y., Leya, I., & Mezger, K. 2015, A&A, 580, A30
Thielemann, F.-K., Nomoto, K., & Hashimoto, M.-A. 1996, ApJ, 460, 408
Tsantaki, M., Sousa, S. G., Adibekyan, V. Z., et al. 2013, A&A, 555, A150
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181
Zhao, G., & Gehren, T. 2000, A&A, 362, 1077

[4] While the C/O ratio controls the amount of Si in carbides and oxides in planets, this ratio may be different to that observed in their host stars atmospheres (Öberg et al. 2011; Thiabaud et al. 2015).