The $T_c$ trend in the $\zeta$ Reticuli system: $N$ spectra – $N$ trends.

V. Adibekyan, 1 P. Figueira, 1 E. Delgado Mena, 1 S. G. Sousa, 1 N. C. Santos, 1,2 J. I. González Hernández, 3,4 G. Israelian 3,4

1 Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal
2 Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Rua do Campo Alegre, 4169-007 Porto, Portugal
3 Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain
4 Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain

Abstract

It is suggested that the chemical abundance trend with the condensation temperature, $T_c$, can be a signature of rocky planet formation or accretion. Recently, a strong $T_c$ trend was reported in the $\zeta$ Reticuli binary system [Saffe et al. 2016], where $\zeta^2$ Ret shows a deficit of refractory elements relative to its companion ($\zeta^1$ Ret). This depletion was explained by the presence of a debris disk around $\zeta^2$ Ret. Later, Adibekyan et al. (2016b) confirmed the significance of the trend, however, raised doubts on the interpretation proposed. Using three individual highest quality spectra for each star, they found that the $T_c$ trends depend on the individual spectra (three spectra of each star were used) used in the analysis. In the current work we re-evaluated the presence and variability of the $T_c$ trend in this system using a larger number of individual spectra. In total, 62 spectra of $\zeta^2$ Ret and 31 spectra of $\zeta^1$ Ret were used. Our results confirm the word of caution issued by Adibekyan et al. (2016b) that nonphysical factors can be at the root of the $T_c$ trends for the cases of individual spectra.

1 Introduction

Stars and planets form and evolve together. This common origin and evolution naturally links some of the properties of stars and planets orbiting them. There are many vivid examples of such a bidirectional link between star–planet evolution: e.g., engulfment of planets due to stellar evolution (e.g., Kunitomo et al. 2011), ejections of planets (leading to free-floating planets) due to close fly-bys (e.g., Hills 1984), white dwarfs atmospheric pollution due to accretion of planets (e.g., Zuckerman et al. 2010), and tidal evolution of close-in planets depending on the properties of the host star (e.g., Bolmont et al. 2017).

Of all the various links and dependences between the properties of stars and planets, the dependence of planet formation and evolution on the chemical properties of the host star (and vice versa) is of particular interest, and is the subject of study in the current manuscript. Detection of only a few hot-Jupiters was enough to pinpoint the first correlation between giant planet occurrence and the host star metallicity (e.g., González 1997, Santos et al. 2001). This dependence, if it exists, is likely very weak for low-mass/small-size planets (e.g., Sousa et al. 2011). The planet occurrence – metallicity correlation had a very important impact on the development of planet formation theories (Ida & Lin 2004, Mordasini et al. 2012, Nayakshin & Fletcher 2015). Later, studies based on large data-sets showed that elements other than iron, such as, C, O, Mg, and Si, may also play a very important role for planet formation (e.g., Robinson et al. 2006, Haywood 2009, Adibekyan et al. 2012a, b, 2015b, 2017b).

Many astronomers, starting from Gonzalez (1997) and Smith et al. (2001), also tried to search for chemical signatures of planet formation and planet accretion on the planet-host stars. In particular, the presence of a trend between the abundances of chemical elements and the condensation temperature of the elements was explored. This trend is usually called $T_c$ trend, and the slope of the correlation of [X/Fe] vs. condensation temperature is usually named $T_c$ slope. Meléndez et al. (2009) were the first to report a statistically significant deficit of refractory elements (high-$T_c$) with respect to volatiles (low-$T_c$) in the Sun when compared to solar twin stars. Together with the rocky material accretion (e.g., Schuler et al. 2011) and/or rocky material in terrestrial planets (e.g., Meléndez et al. 2009), several explanations are proposed to explain the $T_c$ trend. Adibekyan et al. (2014) suggested that the $T_c$ trend strongly depends on the stellar age and they found a tentative dependence on the galactocentric distances of the stars. The correlation with stellar age was later confirmed by several authors (e.g., Nissen 2015, Spina et al. 2016), while the possible relation with the galactocentric distances seems to be more challenging (see Adibekyan et al. 2016a). Maldonado et al. (2015) and Maldonado & Villaver (2016) further suggested a significant correlation with the stellar radius and mass. This very exciting possible connection between chemical peculiarities of parent stars and formation of planets has also been examined in other works (e.g., Ramirez et al. 2009, Biazzo et al. 2015, Saffe et al. 2016, Mishenina et al. 2016, González Hernández et al. 2010, 2013, Teske et al. 2016), but contradictory conclusions were reached. For more discussion and references we refer the reader to Adibekyan et al. (2017a).

Very recently, Saffe et al. (2016) reported a positive $T_c$ trend in the binary system, $\zeta^1$ Ret – $\zeta^2$ Ret, where one of the stars ($\zeta^2$ Ret) hosts a debris disk. The authors explained the deficit of the refractory elements relative to volatiles in $\zeta^2$ Ret
as caused by the depletion of about ~3 $M_{\oplus}$ rocky material. In the following study, Adibekyan et al. (2016b) confirmed the trend obtained by Saffe et al. (2016) using higher S/N data. However, they also found that non-astrophysical factors, such as the quality of spectra employed and errors that are not accounted for, can be responsible for the $T_e$ trends. When using the three highest signal-to-noise (S/N) spectra of each component of the binary system, the authors found significant but varying differences in the abundances of the same star from different individual spectra.

In this work we used larger number of spectra of $\zeta^1$ Ret and $\zeta^2$ Ret to expand on the analysis and perform a double-check on the results obtained in Adibekyan et al. (2016b).

## 2 Data and analysis

The HARPS archive (ESO archive phase 3) contains ~70 and ~170 spectra for $\zeta^1$ Ret and $\zeta^2$ Ret, respectively. From this archive we selected the highest quality spectra for both stars: 31 spectra with S/N $> 150$ for $\zeta^1$ Ret and 62 spectra with S/N $> 250$ for $\zeta^2$ Ret (see Table 1). Then for each individual spectra we derived stellar parameters and chemical abundances. Stellar parameters were derived as in our previous works (e.g. Sousa 2014; Andreasen et al. 2017). We first automatically measured the equivalent widths using the ARES v2 code (Sousa et al. 2015) and then used the grid of ATLAS9 plane-parallel model of atmospheres (Kurucz 1993) and the 2014 version of MOOG (Sousa et al. 2017) to derive parameters under assumption of LTE. The same tools were used to derive chemical abundances of 12 elements following the procedure described in our previous works (e.g. Adibekyan et al. 2012c, 2015c,b). We note that the parameters and abundances are derived with a classical rather than a line-by-line differential approach. In Table 1 we present the mean and standard deviation of obtained values for stellar parameters and chemical abundances of each star. The table shows that in average the spectra-to-spectra dispersion for all the parameters and abundances is very small. However, for individual cases some of the parameters or abundances can be different from the mean value and may have a significant impact on the derived $T_e$ trend.

### Table 1: The mean, standard deviation (of all the measurements) for stellar parameters and chemical abundances derived from individual spectra of $\zeta^1$ Ret and $\zeta^2$ Ret.

| Parameter | $\zeta^1$ Ret | $\zeta^2$ Ret |
|-----------|---------------|---------------|
| N spectra | 31            | 62            |
| S/N       | 3.218±54      | 327±41        |
| $T_{\text{eff}}$ | 5719±10    | 5851±9        |
| log $g$   | 4.51±0.02     | 4.48±0.02     |
| $V_{\text{turb}}$ | 0.88±0.03   | 0.98±0.02     |
| [Fe/H]    | -0.195±0.007  | -0.206±0.007  |
| [Na/H]    | -0.034±0.011  | -0.055±0.014  |
| [Mg/H]    | -0.067±0.013  | -0.078±0.017  |
| [Al/H]    | -0.033±0.014  | -0.076±0.024  |
| [Si/H]    | -0.119±0.011  | -0.130±0.010  |
| [Ca/H]    | -0.044±0.016  | -0.078±0.019  |
| [Sc/H]    | -0.229±0.014  | -0.242±0.018  |
| [<Ti>/H]  | -0.055±0.009  | -0.079±0.009  |
| [V/H]     | -0.173±0.013  | -0.222±0.013  |
| [Cr/H]    | -0.153±0.009  | -0.172±0.011  |
| [Mn/H]    | -0.242±0.023  | -0.303±0.018  |
| [Co/H]    | -0.181±0.012  | -0.21±0.0120  |
| [Ni/H]    | -0.199±0.007  | -0.215±0.008  |

1The last version of ARES code (ARES v2) can be downloaded at [http://www.astro.up.pt/~sousasag/ares](http://www.astro.up.pt/~sousasag/ares).

2The source code of MOOG can be downloaded at [http://www.as.utexas.edu/~chris/moog.html](http://www.as.utexas.edu/~chris/moog.html).

---

Figure 1: *Left:* $[\text{X/H}]$ against condensation temperature for individual spectra of $\zeta^1$ Ret and $\zeta^2$ Ret relative to the Sun. The gray lines represent the results of the linear regression. *Right:* Abundances against condensation temperature for $\zeta^1$ Ret and $\zeta^2$ Ret, derived from each individual spectra relative to the other individual spectra of the same star. The gray lines show the results of the linear regression of the 100 steppes negative and positive trends. The results for $\zeta^1$ Ret are offset by -0.3 dex for a sake of visibility.
Table 2: Slopes of the [X/H] vs. $T_c$ for different pairs of spectra when the most significant positive and negative trends are observed. A frequentist approach is chosen to derive the slopes and their uncertainties.

| Star (S/N: spectra) | Slope±σ | P(F-stat) |
|---------------------|---------|----------|
| $\zeta^2$ Ret (278: HARPS.2010-02-21T00:11:27.058) - $\zeta^2$ Ret (252: HARPS.2008-10-07T05:22:11.508) | -8.24 ± 3.47 | 0.039 |
| $\zeta^2$ Ret (268: HARPS.2008-10-07T05:31:04:470) - $\zeta^2$ Ret (292: HARPS.2009-12-01T01:32:07.799) | 7.59 ± 3.40 | 0.050 |
| $\zeta^1$ Ret (174: HARPS.2007-09-07T09:09:24.860) - $\zeta^1$ Ret (169: HARPS.2004-10-28T07:52:55.573) | 6.39 ± 2.24 | 0.017 |
| $\zeta^1$ Ret (169: HARPS.2004-10-28T07:52:55.573) - $\zeta^1$ Ret (166: HARPS.2005-09-11T09:45:41.214) | -6.86 ± 1.65 | 0.002 |
| $\zeta^2$ Ret (268: HARPS.2008-10-07T05:31:04:470) - $\zeta^1$ Ret (160: HARPS.2007-07-29T10:11:20.240) | 8.49 ± 4.02 | 0.061 |
| $\zeta^2$ Ret (359: HARPS.2008-11-30T03:42:06.702) - $\zeta^1$ Ret (369: HARPS.2005-11-15T03:52:37.899) | -6.65 ± 3.88 | 0.117 |

Note: Units of the slopes are in $10^{-5}$ dex K$^{-1}$.

3 Results

3.1 $\zeta^1$ Ret and $\zeta^2$ Ret vs. Sun

On the left panel of Fig. 1 we show the dependence of [X/H] abundances of $\zeta^1$ Ret and $\zeta^2$ Ret relative to the Sun on the corresponding $T_c$. The 50% $T_c$ equilibrium condensation temperatures for a gas of solar system composition are taken from Lodders (2003). We calculated the slopes with the weighted least-squares (WLS) technique, whereas we calculated the weights as the inverse of the variance (σ$^2$) of the abundance. The p-values come from the F-statistics that test the null hypothesis that the data can be modeled accurately by setting the regression coefficients to zero. We refer the reader to Adibekyan et al. (2016b) for more details. From the figure one can clearly see that depending on the individual spectra the trend can be negative or positive. However, we should note that none of the trends are statistically significant (i.e. different from zero) with the lowest P-value being ~0.17. Interestingly, using very high S/N combined spectra of $\zeta^2$ Ret Adibekyan et al. (2016b) obtained a P-value (using the same F-statistics) of ~0.03 when many elements of wide range of $T_c$ were used. When only elements with $T_c$ > 900 K were used the authors obtained a p-value of 0.7 (i.e., no statistical evidence for the difference from no slope).

3.2 $\zeta^1$ Ret vs. $\zeta^1$ Ret and $\zeta^2$ Ret vs. $\zeta^2$ Ret

On the right panel of Fig. 1 we show the dependence of [X/H] abundances against corresponding $T_c$ for $\zeta^1$ Ret and $\zeta^2$ Ret derived for each individual spectra using all other individual spectra as reference. Again, as for the abundances relative to the Sun, we can see that the sign and significance of the trend depends on the individual spectra used. In Table 2 we provide the results for the most significant trends. The table shows that both negative and positive significant trends can be obtained for each star when individual spectra are used. This result is in good agreement with those obtained in Adibekyan et al. (2016b).

3.3 $\zeta^1$ Ret vs. $\zeta^2$ Ret

Following the same logic, in Fig. 2 we show the dependence of [X/H] abundances against corresponding $T_c$ for individual spectra of $\zeta^2$ Ret relative to $\zeta^1$ Ret. The results are not different from what was obtained in the previous two subsections: combination of different individual spectra lead to different results. We should remind that when the combined higher S/N spectra were used, both Saffe et al. (2016) and Adibekyan et al. (2016b) found a significant abundance difference between $\zeta^2$ Ret and $\zeta^1$ Ret that correlates with $T_c$. We will not compare the exact values of the slopes obtained in the current work and in Saffe et al. (2016) and Adibekyan et al. (2016b), because different number of chemical elements (with a different range of condensation temperature) were used in these works.

4 Conclusion

The $\zeta$ Reticuli binary system is composed of two solar analogs where one of the components ($\zeta^2$ Ret) hosts a debris disk. Saffe et al. (2016) found that the component hosting the debris shows a deficit of refractory-to-volatile elements when compared to its companion. The authors showed that the abundance difference between the two components correlate with the $T_c$. Later Adibekyan et al. (2016b) confirmed this result but also found that the trends (and their significance) obtained in these works depend on the spectra used. We used 31 high-quality (S/N > 150) individual spectra of $\zeta^1$ Ret and 62 high-quality (S/N > 250) individual spectra of $\zeta^2$ Ret to revisit the results obtained in Adibekyan et al. (2016b), namely that the $T_c$ trend depends on the individual spectra used.

Our results show that indeed the $T_c$ trend depends on the
Acknowledgments

V.A. thanks the organizers of EWASS Special Session 4 (2017), Emeline Bolmont & Sergi Blanco-Cuaresma, for a very interesting session and for selecting his oral contribution. This work was supported by Fundação para a Ciência e Tecnologia (FCT) through national funds (ref. PTDC/FIS-AST/7073/2014 and ref. PTDC/FIS-AST/1526/2014) through national funds and by FEDER through COMPETE2020 (ref. POCI-01-0145-FEDER-016880 and ref. POCI-01-0145-FEDER-016886). V.A., E.D.M., F.F., N.C.S., and S.G.S. also acknowledge the support from FCT through Investigador FCT contracts of reference IF/00650/2015/CP1273/CT0001, IF/00849/2015/CP1273/CT0003, IF/0037/2013/CP1191/CT0001, IF/00169/2012/CP0150/CT0002, and IF/00028/2014/CP1215/CT0002, respectively, and POPH/FSE (EC) by FEDER-016886). V.A., E.D.M., P.F., N.C.S., and S.G.S. also acknowledge financial support from the Spanish Ministry project MINECO AYA2014-56359-P. JIGH acknowledges financial support from the Spanish Ministry project MINECO AYA2011-29060. JIGH acknowledges financial support from the Spanish Ministry of Economy and Competitiveness (MINECO) under the 2013 Ramón y Cajal program MINECO RFC-2013-14875, and the Spanish ministry project MINECO AYA2014-56359-P.

References

Adibekyan, V., Delgado-Mena, E., Feltzing, S., González Hernández, J. I., Hinkel, N. R., et al. 2017a, Astronomische Nachrichten, 338, 442.
Adibekyan, V., Delgado-Mena, E., Figueira, P., Sousa, S. G., Santos, N. C., et al. 2016a, A&A, 592, A87.
Adibekyan, V., Delgado-Mena, E., Figueira, P., Sousa, S. G., Santos, N. C., et al. 2016b, A&A, 591, A34.
Adibekyan, V., Figueira, P., Santos, N. C., Sousa, S. G., Faria, J. P., et al. 2015a, A&A, 583, A94.
Adibekyan, V., Gonçalves da Silva, H. M., Sousa, S. G., Santos, N. C., Delgado Mena, E., et al. 2017b, Astrophysics, 60, 325.
Adibekyan, V., Santos, N. C., Figueira, P., Dorn, C., Sousa, S. G., et al. 2015b, A&A, 581, L2.
Adibekyan, V. Z., Benamati, L., Santos, N. C., Alves, S., Lovis, C., et al. 2015c, MNRAS, 450, 1900.
Adibekyan, V. Z., Delgado Mena, E., Sousa, S. G., Santos, N. C., Israelian, G., et al. 2012a, A&A, 547, A36.
Adibekyan, V. Z., González Hernández, J. I., Delgado Mena, E., Sousa, S. G., Santos, N. C., et al. 2014, A&A, 564, L15.
Adibekyan, V. Z., Santos, N. C., Sousa, S. G., Israelian, G., Delgado Mena, E., et al. 2012b, A&A, 543, A89.
Adibekyan, V. Z., Sousa, S. G., Santos, N. C., Delgado Mena, E., González Hernández, J. I., et al. 2012c, A&A, 545, A32.
Andreasen, D. T., Sousa, S. G., Tsantaki, M., Teixeira, G. D. C., Mortier, A., et al. 2017, A&A, 600, A69.
Biazzo, K., Gratton, R., Desidera, S., Lucatello, S., Sozzetti, A., et al. 2015, A&A, 583, A135.
Bolmont, E., Gallet, F., Mathis, S., Charbonnel, C., Amard, L., et al. 2017, A&A, 604, A113.
González, G. 1997, Mon Not R Astron Soc, 285, 403.
González Hernández, J. I., Delgado-Mena, E., Sousa, S. G., Israelian, G., Santos, N. C., et al. 2013, A&A, 552, A6.
González Hernández, J. I., Israelián, G., Santos, N. C., Sousa, S., Delgado-Mena, E., et al. 2010, ApJ, 720, 1592.
Haywood, M. 2009, ApJL, 698, L1.
Hills, J. G. 1984, AJ, 89, 1559.
Ida, S. & Lin, D. N. C. 2004, Astrophys J, 616, 567.
Kunitomo, M., Ikoma, M., Sato, B., Katsuta, Y., & Ida, S. 2011, ApJ, 737, 66.
Kurucz, R. L. 1993, SYNTHE spectrum synthesis programs and line data.
Lodders, K. 2003, ApJ, 591, 1220.
Maldonado, J., Eiroa, C., Villaver, E., Montesinos, B., & Mora, A. 2015, A&A, 579, A20.
Maldonado, J. & Villaver, E. 2016, A&A, 588, A98.
Meléndez, J., Asplund, M., Gustafsson, B., & Yong, D. 2009, ApJL, 704, L66.
Mishenina, T., Kovtyukh, V., Soubiran, C., & Adibekyan, V. Z. 2016, MNRAS, 462, 1563.
Mordasini, C., Albert, Y., Benz, W., Klahr, H., & Henning, T. 2012, Astron Astrophys, 541, A97.
Nayakshin, S. & Fletcher, M. 2015, Mon Not R Astron Soc, 452, 1654.
Nissen, P. E. 2015, A&A, 579, A52.
Ramírez, I., Meléndez, J., & Asplund, M. 2009, A&A, 508, L17.
Robinson, S. E., Laughlin, G., Bodenheimer, P., & Fischer, D. 2006, ApJ, 643, 484.
Saffe, C., Flores, M., Jaque Arancibia, M., Buccino, A., & Jofré, E. 2016, A&A, 588, A81.
Santos, N. C., Israelián, G., & Mayor, M. 2001, Astron Astrophys, 373, 1019.
Schuler, S. C., Plateau, D., Cunha, K., King, J. R., Ghezzi, L., et al. 2011, ApJ, 732, 55.
Smith, V. V., Cunha, K., & Lazzaro, D. 2001, AJ, 121, 3207.
Sneden, C. A. 1973, Carbon and Nitrogen Abundances in Metal-Poor Stars. Ph.D. thesis, THE UNIVERSITY OF TEXAS AT AUSTIN.
Sousa, S. G. 2014, [arXiv:1407.5817].
Sousa, S. G., Santos, N. C., Adibekyan, V., Delgado-Mena, E., & Israelián, G. 2015, A&A, 577, A67.
Sousa, S. G., Santos, N. C., Israelián, G., Mayor, M., & Udry, S. 2011, Astron Astrophys, 533, A141.
Spina, L., Meléndez, J., & Ramírez, I. 2016, A&A, 585, A152.
Teske, J. K., Khanal, S., & Ramírez, I. 2016, ApJ, 819, 19.
Zuckerman, B., Melis, C., Klein, B., Koester, D., & Jura, M. 2010, ApJ, 722, 725.