Detailed abundances of the wide pairs of stars with and without planets: the binary systems 16 Cyg and HD 219542

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Abstract

We present results of the comparative analysis of the two wide binary systems – 16 Cyg, with a giant gas planet orbiting around 16 Cyg B, and HD 219542 without planet detected. Atmospheric parameters of the binary components and the Sun were determined using their high-resolution spectra and the sme tools for automatic spectral analysis. By applying the synthetic spectrum method, we derived abundances of 29 and 23 chemical elements in 16 Cyg and HD 219542, respectively. For 19 of these elements, our results are based on the non-local thermodynamic equilibrium (NLTE) line formation. For both 16 Cyg and HD 219542, we obtained a small abundance difference between the A and B components: +0.019±0.012 and −0.014±0.019, respectively, suggesting only a weak influence of the giant gas planet formation on chemical composition of the host star atmosphere. For HD 219542 A and B, trends of the relative-to-solar abundances with the dust condensation temperature are similar to the literature data for the solar analogues without detected planets. The components of 16 Cyg reveal very similar behaviour of [X/H] with the condensation temperature, however, it is different from that for HD 219542. This indicates a specific chemical composition of the cloud from which the 16 Cyg binary system formed.

Key words: (stars:) binaries: visual – stars: atmospheres – stars: abundances – star: evolution

1 INTRODUCTION

With the development of modern spectroscopic instruments precise abundance studies of the pairs of stars with similar characteristics (spectral class, proper motion, kinematics) including wide binary systems (hereafter wide pairs) as well as comoving pairs became a very important task. The stars in such systems are expected to have a common origin, hence, a common chemical composition. Therefore even small observed abundance differences provide a difficulty for the theory and request a proper explanation. One of the reasons for the chemical inhomogeneity may be an incomplete mixing of the interstellar medium. At the same time, the discovery of the chemically inhomogeneous binary systems where one of the stars is a planet host, allows us to attribute an overall abundance difference between the components to a chemical signature of planet formation.

High precision differential abundance analyses of the stars in wide bound pairs have a potential to discover 'fingerprints' of the confirmed or possible planets and planet formation.

In past years, such studies were performed for both individual pairs and groups of wide pairs with/without detected planets.

Gratton et al. (2001) analysed six wide pairs (separations of few hundreds AU) without detected planets. No abundance difference between the components was found in the four systems, while a significant abundance difference was derived for HD 219542 and HD 200466. This kind of strictly differential abundance analysis was extended to larger groups of wide binaries with the similar solar-like components1 (Desidera et al. 2004, 2006; Nagar et al. 2020; Hawkins et al. 2020; Andrews et al. 2019) and Nelson et al. (2021) tested the abundance consistency for 31 wide binaries and 31 comoving pairs. In both studies, the similar chemistry of the components, at the level of 0.1 dex or even less, was found. However, a differential abundance analysis of the comoving pairs HD 240429/HD 240430 (Oh et al. 2018) and HIP 34407/HIP 34426 (Ramírez et al. 2019) reveals an enhancement of the refractory elements (the dust condensation temperature $T_c > 1200$ K), at the level of up to 0.2 dex. For HD 240429/HD 240430, it was interpreted as an accretion of rocky material by one of the components after the birth. The largest collection consisting of 107 objects was recently analysed by Spina et al. (2021). The authors conclude that about a quarter of the solar-like objects show an excess of the refractory elements in one of the components that may be caused by a planet engulfment event.

Liu et al. (2021) considered some additional effects that can produce the observed relative abundance difference in binary systems. First, an incomplete mixing of the interstellar medium can result in slightly different chemical composition of the binary components. Next is atomic diffusion that alters the surface abundances differ-

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1 We assume here the stars with the effective temperatures ±500-700 K, surface gravity ±0.4 dex and metallicity ±0.3 dex from the solar parameters.
Differentially for different elements in the case of fairly large difference in atmospheric parameters of the components.

Different research groups performing the differential abundance analyses for common wide pairs report sometimes the controversial results. For example, multiple studies were performed for the 16 Cyg system – one of the best studied binaries with detected planets. Schuler et al. (2011) did not find any abundance difference between the two components, while Ramirez et al. (2011) derived a difference of +0.04 dex between A and B, which does not depend on the condensation temperature ($T_c$). Based on the better quality observations obtained with two different spectrographs, Tucci Maia et al. (2014) and Maia et al. (2019) confirmed the result of Ramirez et al. (2011) that 16 Cyg A is more metal rich than 16 Cyg B. However, Tucci Maia et al. (2014) and Maia et al. (2019) got different trends of the relative abundances (A-B) with $T_c$ suggesting a different interpretation of the planet formation effects.

Another example is a wide pair HD 219542 without detected planets. A significant abundance difference of ~0.09 dex between the components was reported by Gratton et al. (2001) and confirmed by Sadakane et al. (2003) who used different spectral observations. However, using the same spectra as Gratton et al. (2001), Desidera et al. (2004) did not find any abundance difference between the components. With another set of spectra, Desidera et al. (2006) confirmed an absence of the metallicity difference.

In all the cited spectroscopic studies, atmospheric parameters of the binary components were derived using the Fe i excitation equilibrium and Fe i/Fe ii ionisation equilibrium methods and the equivalent width measurements. Our practice shows that, in the solar-like and cooler stars of enhanced metallicity, it is very difficult and sometimes impossible to find a reasonable number of the Fe i and Fe ii lines, which are totally free from blending. In the red spectral regions where the atomic line blending is less severe, numerous weak molecular lines start to play an important role.

This study deals with the 16 Cyg and HD 219542 binary systems and aims to perform a detailed abundance analysis of their components. The giant gas planet around 16 Cyg B was discovered by Cochran et al. (1997). The A component of 16 Cyg is itself a close binary, with the M dwarf companion (Raghavan et al. 2006), but no planet detected. No planet was discovered in the HD 219542 binary system. We use the high-quality stellar spectra in a wide spectral region from 4400 to 9000 Å, determine stellar atmosphere parameters with the automatic spectral analysis tools based on a variety of spectroscopic indicators of effective temperature and surface gravity, and, for the first time, derive elemental abundances of 16 Cyg and HD 219542 by the synthetic spectrum method with taking into account the departures from the local thermodynamical equilibrium – LTE (the NLTE approach).

The paper is organized as follows. Observations are described in Section 2 and determinations of stellar atmosphere parameters in Section 3. Abundances of 29 elements in the Sun and the components of the 16 Cyg and HD 219542 binary systems are derived in Section 4. The abundance differences between the stars are discussed in Section 5. Our conclusions are summarised in Section 6.

2 OBSERVATIONS

16 Cyg. Two sets of the high-resolution spectra of the 16 Cyg system were downloaded from the archives. The first one is Canadian Astronomy Data Centre (CADC) archive (Crabtree et al. 1994). The 16 Cyg A and B stars were observed on 2013-06-29 in the frames of the Program 13AB06 with the Echelle SpectroPolarimetric Device for Observation of Stars (ESpAdOnS) spectrograph mounted at the 3.6 m Canada-France-Hawaii Telescope (CHFT, Donati 2003). Spectral resolving power is $R = 81,000$, and wavelength coverage is 3696 – 10482 Å. Total exposure times were 840 s and 1050 s for the A and B components, respectively. Signal-to-noise ratio (S/N) varies from 200 to 500 for different spectral ranges. In addition, we downloaded the spectrum of the solar light reflected from the asteroid Vesta that was observed in the frames of the same observational program. More details on the ESPaDOnS/CFHT spectra of 16 Cyg and Vesta can be found in Tucci Maia et al. (2014).

Spectra of 16 Cyg observed with the High Dispersion Spectrograph (HDS, Noguchi et al. 2002) mounted on the 8.2 m Subaru Telescope of the National Astronomical Observatory of Japan were downloaded from the Subaru Mitaka Okayama Kiso Archive system (SMOKA, Baba et al. 2002). $R = 160,000$ in the visual region. More details on these spectra can be found in Maia et al. (2019).

HD 219542. Spectra of both components were downloaded from the SMOKA archive. They were observed with HDS/Subaru on 2002-12-18 in the frames of the Proposal ID o02201. $R = 89,000$. Total exposure times were 900 s and 1200 s for the A and B components, respectively, resulting in S/N of about 250-350. Wavelength coverage is 4326 – 5821 Å in 35 orders for the blue region and 5695 – 7209 Å in 22 orders for the red region. Spectra were reduced with the help of the MIDAS program complex (Warmels 1992). We used the same spectral data as in Sadakane et al. (2003).

All the downloaded spectra were normalised to the continuum level by fitting a global smooth function to the observed spectrum using a procedure similar to that described in the Appendix A of Rosén et al. (2018). Everywhere except H-lines we used 3rd order polynomial approximation for a smooth function. Comparison between the ESPaDOnS/CFHT and HDS/Subaru spectra of 16 Cyg showed that the latter spectra have a number of gaps between the orders and low S/N in their red part. Therefore we used only the ESPaDOnS spectra in our analysis. Moreover, the resolving power of the ESPaDOnS/CFHT spectra for 16 Cyg is similar to that for the HDS/Subaru spectra of HD 219542. This is favourable for a comparison study of the two systems.

3 ATMOSPHERIC PARAMETERS

For each star, its atmospheric parameters: effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), metallicity ([M/H]), micro- ($\xi$) and macro-turbulent ($\xi_{\text{GT}}$) velocities were obtained with the Spectroscopy Made Easy (SME) IDL program package designed for the automatic spectral analysis (Valenti & Piskunov 1996; Piskunov & Valenti 2017). SME was successfully applied to determinations of the atmospheric parameters and abundances of different stars (Valenti & Fischer 2005; Brewer et al. 2016). The accuracy of the atmospheric parameter determinations with SME was investigated by Ryabchikova et al. (2016) who showed that effective temperatures, surface gravities, and metallicities agree within ±65 K, ±0.12 dex, and ±0.04 dex with other spectroscopic determinations. The SME analysis is based on fitting the synthetic spectra to the observations in chosen spectral regions by varying atmospheric parameters. Simultaneous optimization of free parameters is performed with a $\chi^2$ minimization algorithm described by Marquardt (1963) and Press et al. (1986). This procedure requires a careful choice of spectral lines (line mask) with a different sensitivity to the variations in atmospheric parameters.

The same six spectral regions, that is 4485–4590 Å, 4820–4880 Å (H$\beta$), 5100–5200 Å, 5600–5700 Å, 6100–6200 Å, and 6520–6580 Å (H$\alpha$), and the same line masks as in Ryabchikova et al. (2016) were
Table 1. Atmospheric parameters of the programme stars with the errors estimated by two methods.

| Star          | $T_{\text{eff}}$ | $\sigma_1$ | $\sigma_2$ | log g | $\sigma_1$ | $\sigma_2$ | $[M/H]$ | $\sigma_1$ | $\sigma_2$ | $\xi_1$ | $\sigma_1$ | $\sigma_2$ | $\xi_{\text{eff}}$ | $\sigma_1$ | $\sigma_2$ |
|--------------|------------------|------------|------------|-------|------------|------------|---------|------------|------------|--------|------------|------------|----------------|------------|------------|
| Sun (Vesta)  | 5778             | 70         | 19         | 4.44  | 0.16       | 0.02       | 0.003   | 0.053      | 0.012      | 0.86   | 0.24       | 0.03       | 3.59          | 0.81       | 0.61       |
| 16 Cyg A     | 5829             | 42         | 30         | 4.33  | 0.13       | 0.04       | 0.110   | 0.038      | 0.023      | 0.99   | 0.15       | 0.05       | 4.21          | 0.53       | 0.39       |
| 16 Cyg B     | 5760             | 40         | 34         | 4.39  | 0.11       | 0.04       | 0.074   | 0.033      | 0.024      | 0.90   | 0.14       | 0.06       | 3.32          | 0.54       | 0.39       |
| HD 219542 A  | 5880             | 59         | 32         | 4.39  | 0.19       | 0.05       | 0.104   | 0.049      | 0.027      | 1.08   | 0.13       | 0.05       | 3.89          | 0.58       | 0.32       |
| HD 219542 B  | 5753             | 55         | 37         | 4.47  | 0.16       | 0.05       | 0.134   | 0.049      | 0.030      | 1.01   | 0.13       | 0.06       | 3.41          | 0.56       | 0.57       |

Table 2. Published atmospheric parameters of the programme binary systems.

| Star          | $T_{\text{eff}}$ | log g | $[\text{Fe/H}]$ | Reference       |
|--------------|------------------|-------|------------------|-----------------|
| 16 Cyg        |                  |       |                  |                 |
| A             | B                | A     | B                |                 |
| 5795(20)      | 5760(20)         | 4.30(06) | 4.40(06) | 0.04(02)       | 0.06(02)       | Deliyannis et al. (2000) |
| 5745(40)      | 5685(40)         | 4.21(07) | 4.26(08) | 0.10(03)       | 0.07(03)       | Laws & Gonzalez (2001)   |
| 5825(50)      | 5750(50)         | 4.33(07) | 4.34(07) | 0.096(026)     | 0.052(021)     | Ramírez et al. (2009)    |
| 5813(18)      | 5749(17)         | 4.282(017) | 4.328(017) | 0.103(023)     | 0.069(026)     | Ramírez et al. (2011)    |
| 5796(34)      | 5753(30)         | 4.38(12) | 4.40(12) | 0.076(013)     | 0.053(012)     | Schulier et al. (2011)   |
| 5830(7)       | 5751(6)          | 4.30(02) | 4.35(02) | 0.101(008)     | 0.054(008)     | Tucci Maia et al. (2014) |
| 5816(10)      | 5763(10)         | 4.291(010) | 4.356(010) | 0.093(007)     | 0.062(007)     | Nissen et al. (2017)     |
| 5832(5)       | 5763(5)          | 4.310(014) | 4.360(014) | 0.103(004)     | 0.063(004)     | Maia et al. (2019)       |
| 5839(42)      | 5809(39)         | 4.292(002) | 4.359(002) |                 |                 | White et al. (2013)      |
| 5864(48)      | 5814(59)         | 4.302(014) | 4.373(015) | 0.15(05)       | 0.12(03)       | Metcalfe et al. (2015)   |
| HD 219542     |                  |       |                  |                 |
| A             | B                | A     | B                |                 |
| 5898(50)      | 5713(50)         | 4.37   | 4.38   | 0.293(014)     | 0.201(013)     | Gratton et al. (2001)    |
| 5830(30)      | 5600(30)         | 4.45(10) | 4.40(10) | 0.13(04)       | 0.08(04)       | Sadakane et al. (2003)   |
| 5859(30)      | 5691(30)         | 4.34(10) | 4.42(10) | 0.14(04)       | 0.14(04)       | Desidera et al. (2004)   |
| 5826(30)      | 5674(30)         | 4.32(10) | 4.40(10) | 0.06(04)       | 0.07(04)       | Desidera et al. (2006)   |

Note. Numbers in parenthesis indicate errors in the last digits.

used in the fitting procedure. These regions contain both atomic and molecular lines sensitive to effective temperature variations in solar-like stars (Hγ and Hα lines, Swan system of molecular C2 lines, V1, Ti, Co i lines) as well as the lines sensitive to gravity variations (numerous Ti i-Ti ii and Fe i-Fe ii lines with accurate laboratory line parameters, the Mg i triplet 5167-83 Å). For HD 219542, we implemented two additional regions: 5520-5535 Å and 5710-5716 Å (Mg i). These regions cover the neutral magnesium lines which help in refining the surface gravity being combined with sensitive to the pressure effects. Atomic and molecular line parameters for spectral synthesis were extracted from a recent version of the Vienna Atomic Line Database (VALD3)\(^2\) which provides isotopic and hyperfine structure components of the spectral lines for a number of elements (Pakhomov et al. 2019). The data source for C2 lines is Brooke et al. (2013).

The SME package employs three grids of model atmospheres: ATLAS9 (Castelli & Kurucz 2003), LMLMODELS (Shulyak et al. 2004), and MARCS (Gustafsson et al. 2008). All these models assume plane-parallel (one-dimensional, 1D) geometry and the local thermodynamical equilibrium (LTE). Our calculations were done with the LMLMODELS models because they have a finer grid of the depth points over the atmosphere.

The derived atmospheric parameters are listed in Table 1 together with the error estimates calculated by two methods. The first one ($\sigma_1$) is described in papers by Ryabchikova et al. (2016) and Piskunov & Valenti (2017). It is based on analysis of the cumulative distribution for each free parameter constructed using all pixels selected for fitting by the mask. For each pixel the partial derivative of the synthetic spectrum with respect to the free parameter is computed and the parameter change needed to cancel the difference between synthetic and observed spectrum is estimated. The distribution function usually has very wide wings due to insensitivity of some pixels to the selected parameter variations or due to erroneous/missing atomic and molecular data. However, the central part of the corresponding probability distributions is not too far from a Gaussians (see Fig. 1 and Fig. 2 in Ryabchikova et al. 2016) and, hence, can be used for estimating realistic uncertainties of free parameters. This method assumes that the model errors rather than the measurement uncertainties dominate the resulting values of free parameters. Model errors include data reduction glitches, uncertainties in line data, neglected NLTE effects, errors in assumed instrumental profile, continuum normalisation, etc. The second set of errors ($\sigma_2$) is more of a performance assessment of the optimisation algorithm implemented in SME. It would give realistic uncertainties of the free parameters provided that our model of stellar spectrum is ‘perfect’ in a sense that it will converge to the observations in every wavelength point with increasing S/N of the data. In reality, we have to deal with errors in atomic and molecular data, limitations of atmospheric models, instrumental defects, continuum normalisation, and other systematic issues, thus

\(^2\) http://vald.inasan.ru
We applied comprehensive model atoms from our earlier studies, which are listed in Table 3. The model atoms were build up using the most up-to-date atomic data on energy levels, transition probabilities, photoionization cross-sections, rate coefficients for inelastic collisions with electrons and neutral hydrogen atoms. For C$_1$, the model atom was updated by including the rate coefficients for the C$_1$ + H collisions from Amarsi et al. (2019). In the case of using the approximate Drawinian rates for collisions with H$_1$ (Drawin 1969; Steenbock & Holweger 1984), we applied the scaling factor $S_{H_1}$, which was adopted as $S_{H_1} = 1$ for Ti$_{i-ii}$, $S_{H_1} = 0.5$ for Fe$_{i-ii}$, and $S_{H_1} = 0.1$ for Zr$_{i-ii}$. The coupled radiative transfer and statistical equilibrium equations were solved with a revised version of the detailed code (Giddings 1981; Butler 1984). The update was presented by Mashonkina et al. (2011).

Abundances from individual lines were determined by fitting the synthetic line profiles to the observed spectrum. The synthetic spectra were calculated with the synth$_V$NLTE code (Tsymbal et al. 2019) included in the idl routine binmag6 (Kochukhov 2018). synth$_V$NLTE implements the departure coefficients from detail, allowing us to obtain the best fit to the observed line profile with the NLTE effects taken into account. binmag6 uses the non-linear least-squares fitting code (Markwardt 2009) for free parameters optimization. The influence of the nearby spectral lines is accounted for in the minimization procedure.

For S, Cr, Mn, Co, and Rh, we determined the LTE abundances and calculated the NLTE abundances by applying the NLTE abundance corrections, $\Delta_{\text{NLTE}} = \log e_{\text{NLTE}} - \log e_{\text{LTE}}$, from the literature. For the Si lines, we used $\Delta_{\text{NLTE}}$ from Korotin (2009). For lines of Cr$_{i}$, Mn$_{i}$, and Co$_{i}$, $\Delta_{\text{NLTE}}$ were taken from the NLTE_MPIA website that provides the data from the NLTE calculations of Bergemann & Cescutti (2010, Cr$_{i}$), Bergemann et al. (2019, Mn$_{i}$), and Bergemann et al. (2010, Co$_{i}$). As indicated at the NLTE_MPIA website, the model atom of Co$_{i}$ was updated by including the rate coefficients for the Co$_{i}$ + H$_1$ collisions from quantum mechanical calculations. The departures from LTE can be neglected for lines of Cr$_{ii}$, following conclusions of Bergemann & Cescutti (2010). Korotin (2020) provide the NLTE corrections for lines of Rb$_{i}$.

The lithium NLTE abundances were derived based on the Li$_i$ 6707.8 Å line profile fitting in smfit that implements the grid of the departure coefficients for Li$_i$ pre-calculated according to Lind et al. (2009).

Abundances of the remaining elements (Sc, V, Ni, Cu, Y, La, Ce, Nd, Sm) were determined under the LTE assumption. The NLTE effects for Sc$_{ii}$, Ni$_{ii}$, and Cu$_{i}$ are studied in the literature, however, we did not find the NLTE abundance corrections for the spectral lines and the stars, analysed in this study. For the solar Sc$_{ii}$ lines, $\Delta_{\text{NLTE}} = -0.01$ to $-0.2$ dex for Sc$_{ii}$ 5676, 5669, 5684 Å and $\Delta_{\text{NLTE}} = -0.08$ dex for Sc$_{ii}$ 5526 and 5657 Å, according to Zhang et al. (2008). Minor NLTE effects are found by Shi et al. (2014) for the solar Cu$_{ii}$ lines in the visible spectral range, with $\Delta_{\text{NLTE}} = +0.01$ to $+0.02$ dex, while $\Delta_{\text{NLTE}} = -0.05$ dex for Cu$_{ii}$ 8092 Å. Neither Vieytes & Fontenla (2013), nor Bergemann et al. (2021) report the NLTE abundance corrections for the Ni$_{ii}$ lines analysed in this paper.

We note that accounting for the NLTE effects for our LTE chemical species would affect the abundance differences between the star and the Sun and between the two components of the binary systems by no more than 0.01 dex because of their close atmospheric parameters.

### Table 3. Model atoms used in our NLTE calculations.

| Species | Reference |
|---------|-----------|
| C$_1$   | Alexeeva & Mashonkina (2015) |
| N$_1$   | Neretina (in prep) |
| O$_1$   | Simova & Mashonkina (2018) |
| Na$_1$  | Alexeeva et al. (2014) |
| Mg$_1$  | Mashonkina (2013) |
| Al$_1$  | Mashonkina et al. (2016) |
| Si$_{i-ii}$ | Mashonkina (2020) |
| K$_1$   | Neretina et al. (2020) |
| Ca$_{i-ii}$ | Mashonkina et al. (2017) |
| Ti$_{i-ii}$ | Simova et al. (2016) |
| Fe$_{i-ii}$ | Mashonkina et al. (2011) |
| Zn$_{i-ii}$ | Simova et al. (2022) |
| Zr$_{i-ii}$ | Velichko et al. (2010) |
| Ba$_{i-ii}$ | Mashonkina & Belyaev (2019) |

3 https://nlte.mpia.de/gui-simuC_secE.php

### 4 CHEMICAL ABUNDANCES

#### 4.1 Method of calculations

Abundances of 14 chemical elements (C, N, O, Na, Mg, Al, Si, K, Ca, Ti, Fe, Zn, Zr, Ba) were derived from the NLTE calculations.

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Our test calculations for lines of O I and Ba II in the binaries under investigation showed that, compared with LTE, NLTE reduces the abundance discrepancy between the components A and B. We present also the carbon abundances from the C 2 molecular lines (the Swan band at 5100-5200 Å), which were obtained in the smf procedure. Hereafter, they are denoted as C(mol).

The list of the used atomic lines together with the line data and the references to oscillator strengths \((gf)\), isotopic structure (IS) and hyperfine structure (HFS) data are given in Table 4.

### 4.2 Abundance results

NLTE abundances, \(\log(A) = \log(N_{\text{at}}/N_{\text{tot}})\), from individual lines in the Sun, A and B components of 16 Cyg, and A and B components of HD 219542 are presented in Table 4. They were derived using the atmospheric parameters determined in this study (Table 1).

For 16 Cyg A and B, we also employed \(T_{\text{eff}}/\log g\) derived by Karovicova et al. (2022) from non-spectroscopic methods, namely, effective temperatures based on their own interferometric measurements of stellar diameters and surface gravities based on stellar masses from the Dartmouth stellar evolutionary tracks (Dotter et al. 2008). We note that the adopted \(\log g\) values agree within 0.01 dex with the asteroseismological measurements of Metcalfe et al. (2015) given in Table 2. Hereafter, we refer to these non-spectroscopic atmospheric parameters as interferometric ones, although this is true for the effective temperatures only.

The average elemental abundances, their statistical errors \((\sigma)\), and the number of used lines \((N)\) are presented in Table 5 (Sun, 16 Cyg A, 16 Cyg B) and Table 6 (HD 219542 A, HD 219542 B). Here, \(\sigma\) is the dispersion in the single line measurements about the mean. In order to calculate the mean relative-to-solar abundances, \([X/H]\), we applied a line-by-line differential approach, in the sense that stellar line abundances were compared with individual abundances of their solar counterparts. The abundance differences \([A-B] = [X/H]_A - [X/H]_B\) are also calculated with a line-by-line differential approach. The last column of Table 5 indicates the dust condensation temperatures \(T_c\) for 50% trace element condensation, as calculated by Lodders (2003) for a solar-system chemical composition gas. Actually, metallicity of the program stars is slightly higher than the solar one, by about 0.1 dex. This can lead to a change in \(T_c\) by no more than 30–50 K, according to the simulations by Bond et al. (2010) for extrasolar planetary systems of supersolar metallicity.

The obtained solar abundances are fairly consistent with the most recent solar photosphere (Asplund et al. 2021) and meteoritic (Lodders 2021) abundances. For 28 elements, in common, the average abundance differences (this study – literature) amount to 0.022±0.053 dex and 0.027±0.063 dex, respectively. This is well within the uncertainty of the best solar abundance determinations. The solar abundance comparisons give a credit to our stellar abundance results.

Figure 1 displays the abundance differences between the A and B components of 16 Cyg and HD 219542 and the relative-to-solar abundances of the stars as a function of the dust condensation temperature. Our findings can be formulated as follows.

- In both binary systems, independent of the presence or the absence of the planet, the A and B components do not reveal significant abundance discrepancies, with A – B = 0.019±0.012 dex and –0.014±0.019 dex for 16 Cyg and HD 219542, respectively. This provides a further evidence for a negligible effect of the giant planet formation on atmospheric abundances of the host star (see, for instance, Liu et al. 2014, 2018). Although a slow-growing trend with \(T_c\) and a hint of decreasing (A – B) for \(T_c > 1400\) K are seen for 16 Cyg in the case of using the smf atmospheric parameters. A fairly flat distribution of (A – B) with \(T_c\) is obtained for the interferometric atmospheric parameters. In Sect. 5, we discuss an influence of atmospheric parameters on the abundance trends.

- 16 Cyg and HD 219542 reveal a different behaviour of \([X/H]\) with \(T_c\). For both components of HD 219542, the observed trends are quasi-linear and similar to the trend of \([X/H]\) with \(T_c\) for the solar analogues without detected planets (see Fig. 5 in Meléndez et al. 2009). Both components of 16 Cyg reveal a meaningful step-like change in \([X/H]\) at \(T_c \approx 750\) K, then a decline with increasing \(T_c\) up to \(\approx 1300\) K, and splitting into two trends for the higher \(T_c\). A complex behaviour of \([X/H]\) with \(T_c\) is even more evident for the interferometric atmospheric parameters. See Section 5 for a discussion.

### 5 DISCUSSION

#### 5.1 Li abundances and age estimates

Lithium is of special interest because its deficiency was found in the planet-host atmospheres (King et al. 1997; Gonzalez & Laws 2000). The Li deficiency in 16 Cyg B was confirmed by a number of studies (see references in Table 2), while the atmosphere of 16 Cyg A is more Li rich compared with the solar one. The Li abundance difference between the A and B components in 16 Cyg reaches 0.7 – 0.8 dex.

### Table 4. NLTE abundances from individual lines in the Sun, 16 Cyg A and B components, HD 219542 A and B components together with the line atomic parameters and the references to them.

| Ion        | \(\log(N_{\text{at}}/N_{\text{tot}})\) | \(A, \AA\) | \(E_i, \text{eV}\) | \(\log g f\) | HFS | IS |
|------------|---------------------------------------|-----------|-----------------|-------------|-----|----|
| Sun        | 2 3 4 5 6 7 8 9 10 11 12 13 14        |           |                 |             |     |    |
| Li I       | -10.93 -10.58 -11.29 -10.64 -11.41 -9.84 -10.85 | 6707.764 0.000 -0.002 | YD | BBE | OAO | REB |
| Li I       | 6707.914 0.000 -0.303 | YD | BBE | OAO | REB |
| C I        | -3.575 -3.566 -3.556 -3.603 -3.599 -3.512 -3.553 | 5052.144 7.685 -1.303 | OAO | REB |
| C I        | NIST10 | FIS98 |
| O I        | -3.311 -3.305 -3.288 -3.312 -3.282 -3.253 -3.238 | 6300.304 0.000 -9.720 | FIS98 |

Note. This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content. \(\log g = \log(N_{\text{at}}/N_{\text{tot}}) + 12 = \log((N_{\text{at}}/N_{\text{tot}}) + 12.04)\) in the atmospheres with the solar He abundance. YD = Yan & Drake (1995); BBE = Beckmann et al. (1974); OAO = Orth et al. (1975); REB = Radziemski et al. (1995); NIST10 = Ralphchonko et al. (2010); FIS98 = Fischer et al. (1998). Close blends are marked by colon.
Table 5: Average NLTE abundances of the Sun (Vesta), 16 Cyg A, and 16 Cyg B.

| Elem | Li | C(mol) | C | N | Mg | Al | Na | S | K | Ca | Sc | Ti | Cr | Mn | Fe | Ni | Y | Ba | La | Sm | Eu | Tc |
|------|----|-------|---|---|----|----|----|---|---|----|----|----|----|----|----|---|---|---|---|----|----|----|
| N    | 1  | -10.930.10 | 1 | -10.580.06 | 0.35 | 0.10 | 1 | -11.290.20 | -0.36 | 0.10 | 0.71 | 0.10 | 1 | -10.640.07 | 0.29 | 0.07 | 1 | -11.410.20 | -0.48 | 0.20 | 0.77 | 0.10 |
| σ    | 1  | -3.6220.049 | 2 | -3.5700.029 | 0.052 | 0.029 | 2 | -3.5540.032 | 0.054 | 0.032 | 0.016 | 0.030 | 3 | -3.5220.031 | 0.100 | 0.030 | -3 | -3.5440.028 | 0.078 | 0.030 | 0.022 | 0.030 |
| [X/H] | 0.011 | 0.030 | 0.016 | 0.030 | 0.016 | 0.030 | 0.016 | 0.030 | 0.016 | 0.030 |
| [A-B] | 0.032 | 0.030 | 0.016 | 0.030 | 0.016 | 0.030 | 0.016 | 0.030 | 0.016 | 0.030 |

**Note.** LTE abundances.
Figure 1. Abundance differences between the A and B components of 16 Cyg and HD 219542 (top panels, black circles) and relative-to-solar abundances of the stars (bottom panels) versus the dust condensation temperatures. The results based on the SME atmospheric parameters for 16 Cyg and HD 219542 are shown in the left and right panels. The central panels display the results based on the interferometric atmospheric parameters for 16 Cyg. Linear regressions are shown by solid black lines in the top panels and by solid (primaries) and dashed (secondaries) red lines in the bottom panels.
(see Table 7 in Maia et al. 2019). Even larger difference in Li abundance between the A and B components, of >1 dex, was derived for HD 219542 (Gratton et al. 2001; Sadakane et al. 2003).

For 16 Cyg, we obtained the Li abundance difference \([A-B] = 0.71 \pm 0.10\) and 0.77a±0.10 for two sets of atmospheric parameters, \([A-B] = 1.02\) dex for the HD 219542 system. Our results agree with the literature data in the following aspects: (i) the hotter components of each system have supersolar Li abundance; (ii) the planet-host star 16 Cyg B is deficient in Li; (iii) HD 219542 B without detected planet has close-to-solar Li abundance.

The Li abundance difference as well as the overall metallicity difference between the A and B components of 16 Cyg were attributed to an accretion of planetary material onto 16 Cyg A or the planet engulfment event (Laws & Gonzalez 2001; Maia et al. 2019). However, there may be a different and natural explanation of the difference in Li abundance between the components. First, analysis of stars in the open clusters shows a rapid decrease in the Li abundance with decreasing effective temperature (see Li abundance trends in Fig. 2 of Ryan 2000). For open clusters of \(t = 1.7 - 5\) Gyr, the Li abundance drops from \(\log E_{1\mu} = 2.5\) to 0.6 within a narrow temperature region of \(-200-300\) K. Here, the abundance scale is used where \(\log E_{1\mu} = 12\). Therefore, for both 16 Cyg and HD 219542, the Li abundance difference between the components can be explained by their temperature difference. We produced the plot similar to Fig. 2 in Ryan (2000). In the left panel of Fig. 2, the Li abundance versus \(T_{\text{eff}}\) trends for open clusters of different ages were taken from Hobbs & Pilachowski (1988, NGC 752, \(t = 1.7\) Gyr) and Ryan & Deliyannis (1995, Hyades, \(t = 0.7\) Gyr; M67, \(t = 5\) Gyr). The Li abundances of the planet-host stars were taken from Table 1 of Ryan (2000).

Second, for the solar twin stars (\(T_{\text{eff}} = 5700-5860\) K), the Li abundance drops with increasing stellar age (Carlos et al. 2016), namely, from \(\log E_{1\mu} = 2.2\) to 0.6 over an age interval of \(1 < t < 8\) Gyr. We estimated ages of both systems using their \(log g\) and \(T_{\text{eff}}\) and the isochrones from the single-star MESA (Modules for Experiments in Stellar Astrophysics) theoretical stellar evolution model grid4 (Choi et al. 2016). We checked the isochrone of the solar chemical composition and age of 4.4 Gyr and the isochrones of \([M/H] = +0.1\) dex (right panel of Fig. 2). We estimated \(t = 6 \pm 1\) Gyr for the 16 Cyg system and \(t = 3 \pm 1\) Gyr for HD 219542. Our estimate for 16 Cyg agrees within the error bars with the ages, \(t(A) = 6.80 \pm 0.4\) and \(t(B) = 6.90 \pm 0.28\) Gyr, derived from the astroseismic modelling of Bellinger et al. (2017).

We conclude that the effective temperature difference may explain the Li abundance difference between the components, without involvement a hypothesis of planetary material accretion onto one of the components of binary system. The age difference between the two systems may explain the higher Li abundance of the HD 219542 components compared to those of 16 Cyg.

5.2 Influence of uncertainties in atmospheric parameters on differential abundances

Teske et al. (2015) investigated how the differential abundances in the planet-host binary system XO-2 change with the changes in atmospheric parameters of the components, choice of spectral lines, and methods of spectrum analysis. It was shown that the \(T_{\text{eff}}\) difference plays the major role in shaping the relative abundance versus \(T_{\text{eff}}\) trend that is usually considered as an indicator of the planet formation effects. The slope of the trend may change from positive to negative depending on the size of the effective temperature difference between the components (see Fig. 1 in Teske et al. 2015). Their conclusion is supported by our results. Figure 3 (left panel) displays the Fe abundance difference as a function of the \(T_{\text{eff}}\) difference between the components of 16 Cyg and HD 219542. It is evident that these two parameters reveal a linear correlation. The right panel of Fig. 3 shows how a slope of the \([\text{Fe/H}]_{A-B} = [\text{Fe/H}]_{A} - [\text{Fe/H}]_{B}\) versus \(T_{\text{eff}}\) trend for HD 219542 changes when moving to the largest temperature difference (276 K) between the components derived by Gratton et al. (2001). We conclude from this that the abundance differences derived in some previous studies for the HD 219542 A and B can be removed by revising their atmospheric parameters.

The situation is slightly different for the 16 Cyg system. Except one case in Table 2 with a negative [Fe/H] difference, all the other analyses obtain that 16 Cyg A is marginally more metal-rich than the planet-host star 16 Cyg B, by 0.02 to 0.047 dex. This study obtained the average abundance differences \([A-B] = 0.019\) dex and 0.012 dex, when using the SME and interferometric atmospheric parameters, respectively.

Using the code5 by Galarza et al. (2016), we estimated the mass of rocky material needed to explain the abundance difference between the A and B components of 16 Cyg. First, the code determines the convective mass of the component A for a given atmospheric parameters. Then, for each chemical element, its mass fraction is calculated by adding a mixture from the meteoritic (chondrites, Wasson & Kallemeyn 1988) and terrestrial (Allègre et al. 2001) abundance patterns to that for the B component. The latter is approximated by the solar chemical composition scaled with the overall metallicity of the B component. For more details, see the Appendix in Galarza et al. (2016). We obtained that the slightly higher metallicity of 16 Cyg A compared with 16 Cyg B could be caused by an engulfment of the \(~2\) Earth mass planet composed of the meteoritic (chondrites) like material.

5.3 Trend of abundance differences with the condensation temperature

Meléndez et al. (2009) have discovered the ‘Sun – solar twins’ trend, which is interpreted as a possible effect of the solar system planet formation. Their trend transformed to the ‘solar twins – Sun’ one is reproduced in Fig. 4 together with our abundance trends for 16 Cyg. The \([A-B]\) abundance differences for 16 Cyg are expected to follow the ‘solar twins – Sun’ trend because 16 Cyg B has a planet like the Sun and 16 Cyg A is a solar twin. Both trends in the top panel of Fig. 4 reveal a common behaviour for \(T_{\text{c}} < 1300\) K, however, there is a hint of decreasing \([A-B]\) for \(T_{\text{c}} > 1400\) K, while, in the same \(T_{\text{c}}\) range, the solar twins – Sun differences grow with a bigger slope compared with that for the lower temperatures.

Figure 4 (bottom panel) shows that the [X/H] abundances of 16 Cyg A reveal a different behaviour compared with the ‘solar twins – Sun’ trend. Note that both components of 16 Cyg independent of using either the SME or the interferometric atmospheric parameters reveal very similar trends of [X/H] with \(T_{\text{c}}\). Neither a step-like change in [X/H] at \(T_{\text{c}} \approx 750\) K, nor splitting into two trends for the highest \(T_{\text{c}}\) were detected so far in any of the solar twins.

The 16 Cyg binary system is older than the Sun, and one could expect that it has the lower abundances compared with the solar ones, for example, by 0.07 dex for C and O, by 0.10 dex for S, and by 0.12 dex for Fe, according to the Galactic chemical evolution

4 http://waps.cfa.harvard.edu/MIST/

5 https://github.com/ramstojh/terra
model of Kobayashi et al. (2020). However, 16 Cyg is enhanced in all the elements relative to the Sun. Therefore, the observed features in the [X/H] abundances cannot be explained by the Galactic chemical evolution effects. The similarity of the abundance trends for both components indicates a specific chemical composition of the cloud from which the 16 Cyg binary system formed.

6 CONCLUSIONS

This study deals with the two wide pairs: 16 Cyg A and B, where the secondary component hosts a close-in giant planet, and HD 219542 A and B with no planet detected. Atmospheric parameters of each star and the Sun were determined using the high-quality spectra and the SME tools for automatic spectral analysis. Our method relies on a variety of spectroscopic indicators of effective temperature and surface gravity. A reliability of the method is confirmed by a perfect agreement of $T_{\text{eff}} = 5778$ K and $\log g = 4.44$ derived for the Sun with the canonical solar values.

By applying the synthetic spectrum method, we determined abundances of 29 chemical elements in each component of 16 Cyg, with the NLTE effects taken into account for 19 of them. Abundances of 23 chemical elements were derived for the HD 219542 binary components, with the NLTE abundances for 17 of them. The relative-to-solar abundances $[X/H]$ were calculated by using a line-by-line differential approach. The solar abundances obtained from spectrum of the solar light reflected from the asteroid Vesta appear to be fairly consistent with the most recent solar photosphere (Asplund et al. 2021) and meteoritic (Lodders 2021) abundances.

A careful analysis of the abundance differences between the components [A-B] and the relative-to-solar abundances [X/H] for each binary system leads us to the following conclusions.

- Both binary systems do not reveal significant abundance dis-
crepancies between their A and B components, with the average abundance differences [A-B] = 0.019±0.012 and -0.014±0.019 for 16 Cyg and HD 219542, respectively. This provides an evidence for a negligible effect of the giant planet formation on atmospheric abundances of the host star. Although there is a hint of decreasing [A-B] for the refractory elements with $T_c$ > 1400 K in 16 Cyg.

- For both components of HD 219542, the trends of [X/H] with the dust condensation temperature are quasi-linear and similar to that by Meléndez et al. (2009) for the solar analogues without detected planets.

- 16 Cyg reveals a different behaviour of [X/H]. Both components show a meaningful step-like change in [X/H] at $T_c \approx 750$ K, then a decline with increasing $T_c$ to about 1300 K, and splitting into two trends for the higher $T_c$. Such a similarity of the abundance trends for both components indicates a specific chemical composition of the cloud from which the 16 Cyg binary system formed.

- The differences in the Li abundance between the components, 0.71 dex for 16 Cyg and 1.02 dex for HD 219542, can be explained by the differences in their effective temperatures.

- From our stellar age estimates based on analysis of the isochrones, HD 219542 ($t = 3$ Gyr) is younger than 16 Cyg ($t = 6$ Gyr), and this explains its higher Li abundance.

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DATA AVAILABILITY STATEMENTS

The data underlying this article will be shared on reasonable request to the corresponding author.

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