Letter to the Editor

Signatures of rocky planet engulfment in HAT-P-4*
Implications for chemical tagging studies

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ABSTRACT

Aims. To explore the possible chemical signature of planet formation in the binary system HAT-P-4, by studying abundance vs condensation temperature \( T_c \) trends. The star HAT-P-4 hosts a planet detected by transits while its stellar companion does not have any detected planet. We also study the Lithium content, which could shed light on the problem of Li depletion in exoplanet host stars.

Methods. We derive, for the first time, both stellar parameters and high-precision chemical abundances by applying a line-by-line full differential approach. The stellar parameters were determined by imposing ionization and excitation equilibrium of Fe lines, with an updated version of the FUNDAPAR program, together with ATLAS9 model atmospheres and the MOOG code. We derived detailed abundances of different species with equivalent widths and spectral synthesis with the MOOG program.

Results. The exoplanet host star HAT-P-4 is found to be \(-0.1\) dex more metal rich than its companion, which is one of the highest differences in metallicity observed in similar systems. This could have important implications for chemical tagging studies, disentangling groups of stars with a common origin. We rule out a possible peculiar composition for each star as \( \lambda \) Boötis, \( \delta \) Scuti or a Blue Straggler. The star HAT-P-4 is enhanced in refractory elements relative to volatile when compared to its stellar companion. Notably, the Lithium abundance in HAT-P-4 is greater than in its companion by \(-0.3\) dex, which is contrary to the model that explains the Lithium depletion by the presence of planets. We propose a scenario where, at the time of planet formation, the star HAT-P-4 locked the inner refractory material in planetesimals and rocky planets, and formed the outer giant planet at a greater distance. The refractories were then accreted onto the star, possibly due to the migration of the giant planet. This explains the higher metallicity, the higher Lithium content, and the negative \( T_c \) trend detected. A similar scenario was recently proposed for the solar twin star HIP 68468, which is in some aspects similar to HAT-P-4. We estimate a mass of at least \( M_{\text{rock}} \sim 10 \) M\(_{\text{E}}\) locked in refractory material in order to reproduce the observed \( T_c \) trends and metallicity.

Key words. Stars: abundances – Stars: planetary systems – Stars: binaries – Stars: individual: HAT-P-4, TYC 2569-744-1

1. Introduction

The detection of a possible chemical signature of planet formation in the photospheres of planet host stars is a challenge for the current studies. Several authors attempted to detect this signature by looking at the condensation temperature \( T_c \) trend in planet host stars (e.g. Gonzalez 1997, Smith et al. 2001, Gratton et al. 2001). In particular, Meléndez et al. (2009) showed that the atmosphere of the Sun is deficient in refractory elements when compared to the average abundances of 11 solar twins, also showing a clear \( T_c \) trend. They proposed that the missing refractories are probably locked in terrestrial planets and rocky material that orbits the Sun. This idea was then supported by Ramirez et al. (2009) who studied a sample of 64 solar twins and analogs with and without planets. On the other hand, other authors suggest that the \( T_c \) trends depend on the galactic chemical evolution (GCE), the stellar age or probably the galactic birth place of the stars (e.g. Adibekyan et al. 2014, 2016), competing with the proposed chemical signature of planet formation (e.g. González Hernández et al. 2013).

Most multiple and binary stars are believed to have formed coevally from a common molecular cloud. Wide binaries are particularly valuable, because both components can be presumed to have the same age and initial composition, greatly diminishing the mentioned age and GCE effects. Several studies showed that there may be small differences in the chemical composition of their components, possibly due to the planet formation process (Gratton et al. 2001, Desidera et al. 2004, 2006). The similarity between both components of a binary system made possible to achieve a higher precision in a differential study (e.g. Saffe et al. 2013, 2016). To date, more than 2700 plan-

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1 Refractory and volatile species are those with \( T_c > 900 \) K and \( T_c < 900 \) K.
etary systems have been reported but only a handful of these systems are binaries with similar components. Three of these remarkable systems were studied in detail: 16 Cyg, HAT-P-1 and HD 80606 (Laws & Gonzalez 2001; Ramirez et al. 2011; Schuler et al. 2011; Tucci Maia et al. 2014; Liu et al. 2014; Saffe et al. 2015). There are also binary systems with circumstellar planets orbiting both stars of the system (e.g. Mack et al. 2014). These studies show that a $T\mathrm{e}_{\mathrm{ff}}$ trend is probably present between the stars of 16 Cyg but not in the case of HAT-P-1 nor HD 80606. Notably, the binary system $\zeta$ Ret (where one component is orbited by a dust disk with no planet detected), also shows a $T\mathrm{e}_{\mathrm{ff}}$ trend between their stars, supporting the chemical signature of planet formation (Saffe et al. 2016). Then, there is a clear need of additional systems to be studied through detailed abundance analyses in order to reach more significant conclusions.

As a result of the planetary transit survey HATNet, Kovács et al. (2007) discovered a giant planet of 0.68 $M_{\text{Jup}}$, orbiting the star HAT-P-4 ($=BD +36 2593$) at a distance of 0.04 AU. They estimated a density of 0.41 $\text{g cm}^{-3}$, being one of the lowest density hot Jupiters known. Then, Mugrauer et al. (2014) showed that HAT-P-4 forms a wide binary system separated 91.8 arcsec from its companion (TYC 2569-744-1, hereafter component B), and showed that both stars present very similar spectra (GOV + G2V). The estimated separation is 28446 AU, being considered by Mugrauer et al. (2014) as a true binary system based in their common proper motion and similar radial velocity. To date, there is no planet detected around the B star, being also included in the field G191 (FOV = 8 $\times$ 8 deg) of the HATNet survey (Kovács et al. 2007). As we show in the next sections, the stellar parameters of both stars are very similar, making this system an ideal case to study the possible chemical signature of planet formation.

Different authors have shown a possible excess of Li depletion in stars with planets, when compared to stars without planets (King et al. 1997; Israelian et al. 2004, 2009; Delgado-Mena et al. 2015; Gonzalez 2014, 2015). The Li depletion was first attributed to the presence of planets, by possibly increasing the angular momentum of the star (e.g. during planet migration) and increasing its convective mixing (Israelian et al. 2009). On the other hand, some works show that the Li depletion is related to a bias in age, mass and metallicity, and not due to the presence of planets nor the planet formation process (Lock & Héiter 2006; Baumann et al. 2012; Ramirez et al. 2012; Carlos et al. 2016). The study of similar stars in binary systems can help to understand the origin of Li depletion. In the 16 Cyg binary system, the B component hosts a planet of 1.5 $M_{\text{Jup}}$ (Cochran et al. 1997) and presents a Li content ~4 times lower than the A star (King et al. 1997), supporting the model of Li depletion by the presence of planets. However, Ramirez et al. (2011) showed that the slightly different mass of stars A and B could explain its different Li content i.e. 16 Cyg in principle can support both scenarios. Notably, HAT-P-4 is in some way complementary to 16 Cyg: in this case, the planet host star presents the higher Li content, which is contrary to the model of Li depletion due to the presence of planets. Then, it is worthwhile exploring both the $T\mathrm{e}_{\mathrm{ff}}$ trends and the Li depletion in this remarkable system.

2. Observations and data reduction

Observations of HAT-P-4 binary system were acquired through GRACES (Gemini Remote Access to CFHT ESPaDOnS Spectrograph). This device takes advantage of the high-resolution ESPaDOnS spectropolarimetric system, located at the Canada-France-Hawaii Telescope (CFHT) and fed by an optical fiber connected to the 8.1 m Gemini North telescope at Mauna Kea, Hawaii. We used the 1-fiber object-only observing mode which provides an average resolving power of ~67500 between 4500 and 8500 Å. The stellar spectra were obtained under a Fast Turnaround (FT) observing mode requested to the Gemini Observatory (program ID: GN-2016A-FT-25, PI: C. Saffe). The observations were taken on June 3, 2016, with the B star observed immediately after the A star, using for both the same spectrophotometer configuration. The exposure times were 2 $\times$ 17 min on each target, obtaining a final signal-to-noise ratio of S/N $\sim$400 measured at ~6000 Å in the combined spectra. The final spectral coverage is 4050-10000 Å. The Moon was also observed with the same spectrophotogram set-up, achieving a similar S/N to acquire the solar spectrum as initial reference. GRACES spectra were reduced using the code OPERA\textsuperscript{4} (Martìoli et al. 2012). More recent documentation on OPERA can be found at the ESPERPECTO project webpage\footnote{Kurucz 1993}.

3. Stellar parameters and abundance analysis

Table 1. Stellar parameters derived for each star.

| (Star - Reference) | $T_{\text{eff}}$ | $\log g$ | $[\text{Fe/H}]$ | $v_{\text{rotation}}$ |
|-------------------|---------------|---------|----------------|------------------|
| (A - Sun)         | 6058 ± 65     | 4.39 ± 0.13 | 0.397 ± 0.005 | 1.29 ± 0.09 |
| (B - Sun)         | 6037 ± 68     | 4.38 ± 0.14 | 0.175 ± 0.006 | 1.21 ± 0.07 |
| (A - B)           | 6035 ± 66     | 4.39 ± 0.10 | 0.105 ± 0.006 | 1.22 ± 0.06 |

Fundamental parameters ($T_{\text{eff}}, \log g, [\text{Fe/H}], v_{\text{rotation}}$) were derived following a similar procedure to our previous work (Saffe et al. 2015, 2016). We measured the equivalent widths (EW) of Fe\,i and Fe\,ii lines by using the IRAF task iplot, and then continued with other chemical species. Both the lines list and relevant laboratory data were taken from literature (Liu et al. 2014; Meléndez et al. 2014, Bedell et al. 2014). We imposed excitation and ionization balance of Fe lines, using the differential version of the FUNDPAR program (Saffe et al. 2011, Saffe et al. 2015). This code made use of ATLAS9 model atmospheres (Kurucz 1993) together with the 2014 version of the MOOG program (Sneden 1973). Stellar parameters were determined using the Sun as reference i.e. (A - Sun) and (B - Sun), by adopting (5777 K, 4.44 dex, 0.00 dex, 0.91 km/s) for the Sun\textsuperscript{3}. Then, we recalculated the parameters using the A star as reference i.e. (B - A), by adopting for the A star the parameters derived for the case (A - Sun) (see Table 1). The errors in the stellar parameters were derived following the procedure detailed in Saffe et al. (2015), which takes into account the individual and the mutual covariance terms of the error propagation. Within the errors, the parameters of the B star agree using the Sun or the A star as reference. We note that the A star is ~0.1 dex more metal rich than the B star. Figure 1 shows abundance vs excitation potential (top panel) and abundance vs EW, (bottom panel), both for the case (B - A).

The next step was the derivation of abundances for all remaining chemical elements. The hyperfine structure splitting

\footnote{Echelle SpectroPolarimetric Device for the Observation of Stars}

\footnote{http://www.gemini.edu/sciops/instruments/graces/spectroscopy/spectral-range-and-resolution}

\footnote{Open source Pipeline for ESPaDOnS Reduction and Analysis}

\footnote{http://wiki.lna.br/wiki/spectro}

\footnote{We estimated a $v_{\text{rotation}}$ of 0.91 km/s for the Sun by requiring zero slope between Fe\,i abundances and EW,}

\footnote{http://exoplanet.eu/catalog/}

\footnote{Article number, page 2 of 5}
(HFS) was considered for V i, Mn i, Co i, Cu i and Ba ii using the HFS constants of Kurucz & Bell (1995) and performing spectral synthesis for these species. We also derived the Li i abundance by using spectral synthesis with the resonance line 6707.80 Å which includes the doublet 6707.76 Å, 6707.91 Å and HFS components. We corrected Na i abundance by NLTE (Non-Local Thermodynamic Equilibrium) effects, interpolating in the data of Shi et al. (2004) and adopting Na(NLTE) - Na(LTE) ∼ -0.07 dex for each star. We also applied NLTE corrections to O i (-0.18 dex and -0.17 dex for the A and B stars), by interpolating in the data of Ramírez et al. (2007). These corrections are relative to the Sun, which implies that NLTE effects for the case (B - A) are not significative given the high similarity between the stars A and B.

4. Results and discussion

Condensation temperatures were taken from the 50% T c values derived by Lodders (2003) for a solar system gas with [Fe/H]=0. As suggested by the referee, it would be helpful the calculation of other T c sequences for different metallicity values. We corrected by GCE effects for the case (star - Sun) but not for the case (B - A), by adopting the GCE fitting trends of González Hernández et al. (2013) i.e. following the same procedure of Saffe et al. (2015). Figure 2 presents the corrected abundance values vs T c for (A - Sun). Table 2 presents the slopes and uncertainties of the linear fits. The positive slopes for the case (star - Sun) indicate a higher content of refractories (those with T c > 900 K) relative to volatiles (T c < 900 K).

The differential abundances for (B - A) are presented in Figure 3. The continuous line in this Figure presents the solar-twins trend of Meléndez et al. (2009) (vertically shifted). Long-dashed lines are weighted linear fits to all species and to refractory species. The solar-twins trend of Meléndez et al. (2009) is shown with a continuous line.

4.1. Do HAT-P-4 stars have a peculiar composition?

We detected a difference of ∼0.1 dex in metallicity between the stars A and B, which is one of the highest differences found in similar systems (e.g. Desidera et al. 2004, 2006). In this section we discuss the possible chemical pattern of both stars. λ Boötis stars show moderate surface underabundances of most Fe-peak elements, but solar abundances of C, N, O and S (e.g. Paunzen 2004), in contrast to the metal-rich content of stars A and B.
δ Scuti stars are pulsating variables with \( \sim \) A6-F6 spectral types and mass between 1.4-3.0 \( M_\odot \) (see e.g. the catalogs of Rodríguez et al. [2000], Liakos & Niarchos [2017]). We determined the stellar masses through a Bayesian method using the PARSEC isochrones (Bressan et al. [2012]), obtaining 1.24 ± 0.06 \( M_\odot \) and 1.17 ± 0.05 \( M_\odot \) for the stars A and B. Both the temperature and mass of A and B are lower than all δ Scuti stars of these catalogs. One of the coolest δ Scuti stars with abundance determination is CP Boo (6320 K, Galeev et al. [2012]), which is \( \sim \) 300 K hotter than the A star. However, the A star is enhanced (\( \geq 0.20 \) dex) in Na, Mg, Al, Sc, V, and strongly enhanced (\( > 0.40 \) dex) in Sr and Y compared to CP Boo. Also, the stars A and B lie out of the instability strip boundaries (e.g. Figures 6 and 7 of Liakos & Niarchos [2017]) and no stellar pulsations have been reported.

Blue stragglers (BS) are stars significantly bluer than the main-sequence turnoff of the cluster (or population) to which they belong. There are binaries where one component is BS, being impossible to fit both components with a single isochrone (Desidera et al. [2007]). However, in our system the ages of both stars agree within the errors (2.7 ± 1.3 Gyr and 2.9 ± 1.8 Gyr), also derived with the PARSEC isochrones (Bressan et al. [2012]). BS stars present significant rotational velocities, intense activity and very low Li content (e.g. Fuhrmann & Bernkopf [1999], Schirbel et al. [2015], Ryan et al. [2001]). None of these characteristics are seen in the stars A or B.

There are no firm reasons to identify any component of the binary system as peculiar. Then, a possible different accretion would be the most plausible explanation for the chemical differences observed. We estimated the rocky mass of depleted material in the A star following Chambers [2010]. Adopting a convective zone similar to the present Sun (\( M_\odot = 0.023 M_\odot \)) we obtain \( M_{\text{rock}} \sim 10 M_\oplus \). However, adopting a higher \( M_\odot \) value (e.g. 0.050 \( M_\odot \)) at the time of planet formation, we derive \( M_{\text{rock}} \sim 20 M_\oplus \) (Cody & Sasselov [2005]) found that for stars with 1.1 \( M_\odot \), a polluted convective zone is slightly smaller (\( \sim 1 \% \)) than its unpolluted counterpart, however the trend is reversed for stars with \( M < M_\odot \). More recently, Van Saders & Pinsonneault [2012] found that the acoustic depth to the base of the CZ varies at the 0.5–1% per 0.1 dex level in \([Z/X] \). A change of 1% in \( M_\odot \) translates into \( \sim 0.5 M_\oplus \) of derived accreted material. Then, the estimation of at least 10 \( M_\oplus \) of accreted material should be considered as a first order approximation.

### 4.2. The hot Jupiter planet and the Lithium content

The formation of hot Jupiter planets is mainly explained by the model of core accretion (Pollack et al. [1996]), and by gravitational instability (Boss [2000]). In both cases, some kind of migration from the original location is required to explain the current orbit at \( \sim 0.04 \) AU, with the possible accretion of inner planets into the star (e.g. Mustill et al. [2015]). Other possibility is the “in situ” formation of the hot Jupiter (e.g. Bodenheimer et al. [2003], without migration from greater distances. However, abundances of C/O and O/H ratios suggest that some hot Jupiters originate beyond the snow line (Breuer et al. [2017]), with the present data, it is difficult to disentangle between the different formation scenarios. Additional planets were searched in the A star by transits (Smith et al. [2009], Ballard et al. [2011]) and radial velocity (Knutson et al. [2014]), with no success. Then, a scenario with a possible migration and accretion could not be discarded.

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\(^9\) http://stev.oapd.inaf.it/cgi-bin/param_1.3

![Fig. 4. Stellar spectra near the Lithium line 6707.8 Å for the A (blue dotted line) and B (black continuous line) stars.](image-url)
4.4. Possible interpretations of the data

We propose that at the time of planet formation, the A star locked the orbiting refractory material in planetesimals and rocky planets, and formed the gas giant in the external disk. This is followed by the accretion of most of the refractories (possibly due to migration of the gas giant) onto the A star. This scenario explains the higher metallicity of the A star (no chemically peculiar patterns are seen), the higher refractory abundances and the higher Li content. It is also supported by the slightly higher mass of the A star (corresponding to a lower convective mass and lower mixing of the accreted material), and by the non-detection of additional inner planets. A very similar scenario was recently proposed for the solar twin star HIP 68468 (Meléndez et al. 2017), where the authors suggest that the possible inward migration of a close-in giant planet likely produces the engulfement of the inner planetary material by the star. This would explain the high Li content (0.6 dex greater than expected for its age), a refractory enhancement compared to the Sun and a $T_{\text{eff}}$ trend. We also note that chemical tagging studies usually claim to be able to disentangle groups of stars with common origin within ~0.04 dex of precision (e.g. Hogg et al. 2016). Then, an intrinsic difference of ~0.1 dex in metallicity would imply a great challenge for these works.

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Fig. 5. Spectral region near the Hα line for the stars A and B (blue dotted and black continuous line). A synthetic spectra (red dashed line) with $T_{\text{eff}}$(A) - 150 K = 5886 K is also showed for comparison.

Fig. 6. Differential abundance vs excitation potential (upper panel) and vs reduced EW (lower panel) for the A star, adopting $T_{\text{eff}}$(A) - 150 K = 5886 K. Filled and hollow circles correspond to FeI and FeII.

Article number, page 5 of 5