A detailed spectropolarimetric analysis of the planet-hosting star WASP-12

Journal Item

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L. Fossati

Department of Physics and Astronomy, Open University, Walton Hall, Milton Keynes MK7 6AA, UK

l.fossati@open.ac.uk

and

S. Bagnulo

Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland, UK

sba@arm.ac.uk

and

A. Elmasli[3] and C. A. Haswell and S. Holmes

Department of Physics and Astronomy, Open University, Walton Hall, Milton Keynes MK7 6AA, UK

elmasli@ankara.edu.tr,C.A.Haswell@open.ac.uk,s.holmes@open.ac.uk

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and

O. Kochukhov

Department of Physics and Astronomy, Uppsala University, SE-751 20, Uppsala, Sweden

Oleg.Kochukhov@fysast.uu.se

and

E. L. Shkolnik

Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015, USA

shkolnik@dtm.ciw.edu

and

D. V. Shulyak

Institute of Astrophysics, Georg-August-University, Friedrich-Hund-Platz 1, D-37077, Göttingen, Germany

denis.shulyak@gmail.com

and

D. Bohlender

Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada

david.bohlender@nrc-cnrc.gc.ca

and

B. Albayrak

Department of Astronomy and Space Sciences, Ankara University, 06100, Tandoğan, Ankara, Turkey

balbayrak@ankara.edu.tr

and

C. Froning

Center for Astrophysics and Space Astronomy, University of Colorado, 593 UCB, Boulder, CO 80309-0593, USA

cynthia.froning@colorado.edu

and

L. Hebb

Department of Physics and Astronomy, Vanderbilt University, 6301 Stevenson Center Nashville, TN 37235, USA

leslie.hebb@vanderbilt.edu

Received ______________; accepted ______________

[3]Department of Astronomy and Space Sciences, Ankara University, 06100, Tandoğan, Ankara, Turkey

ABSTRACT

The knowledge of accurate stellar parameters is paramount in several fields of stellar astrophysics, particularly in the study of extrasolar planets, where often the star is the only visible component and therefore used to infer the planet's fundamental parameters. Another important aspect of the analysis of planetary systems is the stellar activity and the possible star-planet interaction. Here we present a self-consistent abundance analysis of the planet hosting star WASP-12 and a high-precision search for a structured stellar magnetic field on the basis of spectropolarimetric observations obtained with the ESPaDOnS spectropolarimeter. Our results show that the star does not have a structured magnetic field, and that the obtained fundamental parameters are in good agreement with what was previously published. In addition we derive improved constraints on the stellar age (1.0–2.65 Gyr), mass (1.23–1.49 $M/M_{\odot}$), and distance (295–465 pc). WASP-12 is an ideal object to look for pollution signatures in the stellar atmosphere. We analyse the WASP-12 abundances as a function of the condensation temperature and compare them with those published by several other authors on planet hosting and non-planet hosting stars. We find hints of atmospheric pollution in WASP-12's photosphere, but are unable to reach firm conclusions with our present data. We conclude that a differential analysis based on WASP-12 twins will probably clarify if an atmospheric pollution is present, the nature of this pollution and its implications in the planet formation and evolution. We attempt also the direct detection of the circumstellar disk through infrared excess, but without success.

Subject headings: stars: individual (WASP-12) — stars: abundances — stars: magnetic field — stars: fundamental parameters

1. Introduction

One of the biggest surprises in the exoplanet field was the discovery of gas giant planets orbiting very close to their host star. These hot Jupiter planets represent one extreme of the Galaxy's population of planets, and they provide important constraints to guide our nascent ideas about the formation and evolution of planetary systems. The probability of transit for close-in giant planets is $\sim$ 10% (Seager et al. 2000), and through the analysis of transit light curves the ratio of the stellar and planetary radii can be deduced. Through the significant uncertainties in the mass and radius of any particular star, our characterisation of exoplanets is limited by that of their host stars (e.g. Southworth 2009). For this reason, it is important to directly measure the properties of planet hosting stars, particularly in cases where we expect the presence of planets may have influenced the properties of the star through star-planet interactions.

One of the most extreme hot Jupiter exoplanets is WASP-12 b, a gas giant planet orbiting only 0.023 AU from a late F-type host star (Hebb et al. 2009). WASP-12 b's orbit is, therefore, only about 1.5 stellar diameters from the photosphere of the star. At such proximity, interactions between the star and the planet must occur. Near-UV observations of WASP-12 covering the wavelengths of many resonance lines reveal that WASP-12 b is surrounded by an exosphere which appears to overfill its Roche lobe (Fossati et al. 2010). This exospheric gas may be the consequence of tidal disruption of the planet's convective envelope as recently suggested by Li et al. (2010), but it could also be entrained material from the stellar corona.

A planet orbiting as close as WASP-12 b might be expected to interact magnetically with its host star, c.f. Shkolnik et al. (2003), Shkolnik et al. (2005), and Shkolnik et al. (2008). A first step to search for such interactions is to detect and quantify the stellar magnetic field by spectropolarimetry, e.g. Fares et al. (2010). The presence of a magnetic field belonging to WASP-12 would provide a precious piece of information needed to establish which mechanism controls the structure and the evolution of the disk (Lai et al. 2010).

The solar system's giant planets have enhanced metal abundances relative to the Sun (Guillot 2005) and high atmospheric metal abundances have been suggested as a contributing factor in the inflated radii of planets such as WASP-12 b (Burrows et al. 2007). Intriguingly, Fossati et al. (2010) detected a wealth of metallic atoms and ions in the exospheric gas surrounding WASP-12 b. If this gas is indeed accreting onto the host star as suggested by Li et al. (2010), this could lead to abundance anomalies in the photosphere of WASP-12. Since WASP-12 is expected to have a very shallow surface convection zone, any accreted gas will remain close to the surface rendering any pollution of the surface composition relatively easy to detect.

In this paper, we report on spectropolarimetric observations of WASP-12 which we use to probe the stellar magnetic field, fundamental parameters and abundance pattern of the star. In Sect. 2 we describe our observations and data reduction. Sect. 3 and Sect. 4 provide a description of the adopted model atmosphere including methods and results of the stellar parameter determination and abundance analysis. In Sect. 5 we provide the results of our stellar magnetic field search. Our results are finally discussed in Sect. 6, while in Sect. 7 we gather our conclusions.

2. Observations and data reduction

We observed WASP-12 using the ESPaDOnS (Echelle SpectroPolarimetric Device for ObservatioNs of Stars) spectropolarimeter at the Canada-France-Hawaii Telescope (CFHT) on the 3rd and 5th of January 2010. The observations were performed in "polarimetric" mode.

ESPaDOnS consists of a table-top cross-dispersed echelle spectrograph fed via a double optical fiber directly from a Cassegrain-mounted polarisation analysis module. Beside the natural intensity I, in polarimetric mode the instrument can acquire a Stokes V (or Q or U) profile throughout the spectral range 3700–10400 Å with a resolving power of about 65 000. A complete polarimetric observation consists of a sequence of 4 sub-exposures (Donati et al. 1997; Wade et al. 2000).

Each of the four sub-exposures was 1290 seconds long, with a total amount of integration time of 1.5 hrs, each night. The spectra were reduced using the Libre-ESpRIT package[1] (Donati et al. 2007). The Stokes I spectra have a signal-to-noise ratio (SNR) per pixel of ~126 and ~158 in the continuum, on the first and second nights respectively; both values calculated at 5000 Å. To increase the SNR of the Stokes I spectrum we averaged the two available spectra, obtaining a single spectrum with a SNR of ~200, normalised by fitting a low order polynomial to carefully selected continuum points.

The effective temperature ($T_{\rm eff}$) was determined (see Sect. 4) from our ESPaDOnS data and two spectra of WASP-12 obtained at the Isaac Newton Telescope (INT) with the Intermediate Dispersion Spectrograph (IDS). The spectra cover the region of the Hα line with a spectral resolution of R=8 000 (see Hebb et al. 2009, for more details).

We also used Near-UV observations obtained with the HST Cosmic Origin Spectrograph (COS) (Green et al. 2010; Osterman et al. 2010) for the analysis of the spectral energy distribution. The spectra, calibrated in flux, cover three non-contiguous wavelength ranges in the Near-UV with a resolution of R ~20 000. These observations are described in detail in Fossati et al. (2010).

3. The model atmosphere

To compute model atmospheres of WASP-12 we employed the LLmodels stellar model atmosphere code (Shulyak et al. 2004). For all the calculations Local Thermodynamical Equilibrium (LTE) and plane-parallel geometry were assumed. We used the VALD database

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[1] www.ast.obs-mip.fr/projets/espadons/espadons.html

(Piskunov et al. 1995; Kupka et al. 1999; Ryabchikova et al. 1999) as a source of atomic line parameters for opacity calculations. The recent VALD compilation contains information for about 6.6×10^7 atomic transitions, most of them coming from the latest theoretical calculations performed by R. Kurucz[2]. Convection was implemented according to the Canuto & Mazzitelli (1991, 1992) model of convection (see Heiter et al. 2002, for more details).

4. Fundamental parameters and abundance analysis

Hebb et al. (2009) derived the fundamental parameters of WASP-12 from the analysis of low and mid-resolution spectra, obtaining $T_{\rm eff}$=6300±150 K, $\log g$=4.38±0.10, and adopting a value of 0.85 km s^{-1} for the microturbulence velocity ($\upsilon_{\rm mic}$). We used these values as our starting point in an iterative process to gradually improve the parameters using different spectroscopic indicators. In our analysis, every time any of $T_{\rm eff}$, $\log g$, $\upsilon_{\rm mic}$ or abundances changed during the iteration process, we recalculated a new model with the implementation of the last measured quantities. Similarly the derived abundances were treated iteratively: while the results of the abundance analysis depend upon the assumed model atmosphere, the atmospheric temperature-pressure structure itself depends upon the adopted abundances, so we recalculated the model atmosphere every time abundances were changed, even if the other model parameters were fixed. This ensures the model structure is consistent with the assumed abundances.

We determined $T_{\rm eff}$ by fitting synthetic line profiles, calculated with SYNTH3 (Kochukhov 2007), to the observed profiles of two hydrogen lines: Hα (from the IDS spectrograph) and Hγ (from the ESPaDOnS spectropolarimeter). We discarded the other hydrogen lines observed with ESPaDOnS because of the uncertainties in the continuum normalisation. In the temperature range expected for WASP-12, hydrogen lines are extremely sensitive to temperature variations

[2]http://kurucz.harvard.edu

and insensitive to $\log g$ variations, and are therefore good temperature indicators. We found $T_{\rm eff}$=6250±100 K, in good agreement with Hebb et al. (2009). The uncertainty estimate considered both the quality of the observations and the uncertainties in the normalisation. Figure 1 shows the comparison between the observed Hα line profile and the synthetic profiles calculated with the adopted $T_{\rm eff}$ of 6250±100 K. The poor fit of the hydrogen line core is due to the adopted LTE approximation (see e.g. Mashonkina et al. 2009).

Another spectroscopic indicator for $T_{\rm eff}$ is given by the analysis of metallic lines, that we performed on the ESPaDOnS spectrum. In particular, $T_{\rm eff}$ is determined by eliminating the correlation between abundance and excitation potential ($\chi_{\rm excit}$) for the selected lines of a given ion/element. The top panel of Fig. 2 shows the correlation between abundance and $\chi_{\rm excit}$ for all measured lines of Ca I, Ca II, Fe I, Fe II, and Ni I. Figure 2, produced using the final adopted fundamental parameters, shows no significant correlation between abundance and $\chi_{\rm excit}$ for all ions, except Fe I, for which we registered a slightly positive correlation (0.02263±0.01139), that would be eliminated by a higher $T_{\rm eff}$. What we found here for Fe I resambles what remarked by Ryabchikova et al. (2009) for HD 49933 and HD 32115 (both stars have a $T_{\rm eff}$ slightly higher than WASP-12): an effective temperature determination based only on the analysis of Fe I lines leads systematically to a $T_{\rm eff}$ that is substantially higher (by about 5%), compared to the one obtained with other ions and in particular with other temperature indicators, such as hydrogen lines [3]. For this reason, we decided to use the analysis of the metallic lines only as consistency check of $T_{\rm eff}$ derived from the hydrogen lines. In addition to the ions shown in Fig. 2, we included in the consistency check also C I, Si I, Sc II, Ti I, Ti II, V I, Cr I, Cr II, Mn I, Co I, and Y II,

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[3]We do not know the precise origin of this phenomenon and also whether it is present in a large temperature range or just for F-type stars. We believe that more work should be done in this respect, in particular because the $T_{\rm eff}$ determination based on the abundance-$\chi_{\rm excit}$ equilibrium is widely used to determine the effective temperature of stars in a broad $T_{\rm eff}$ range.

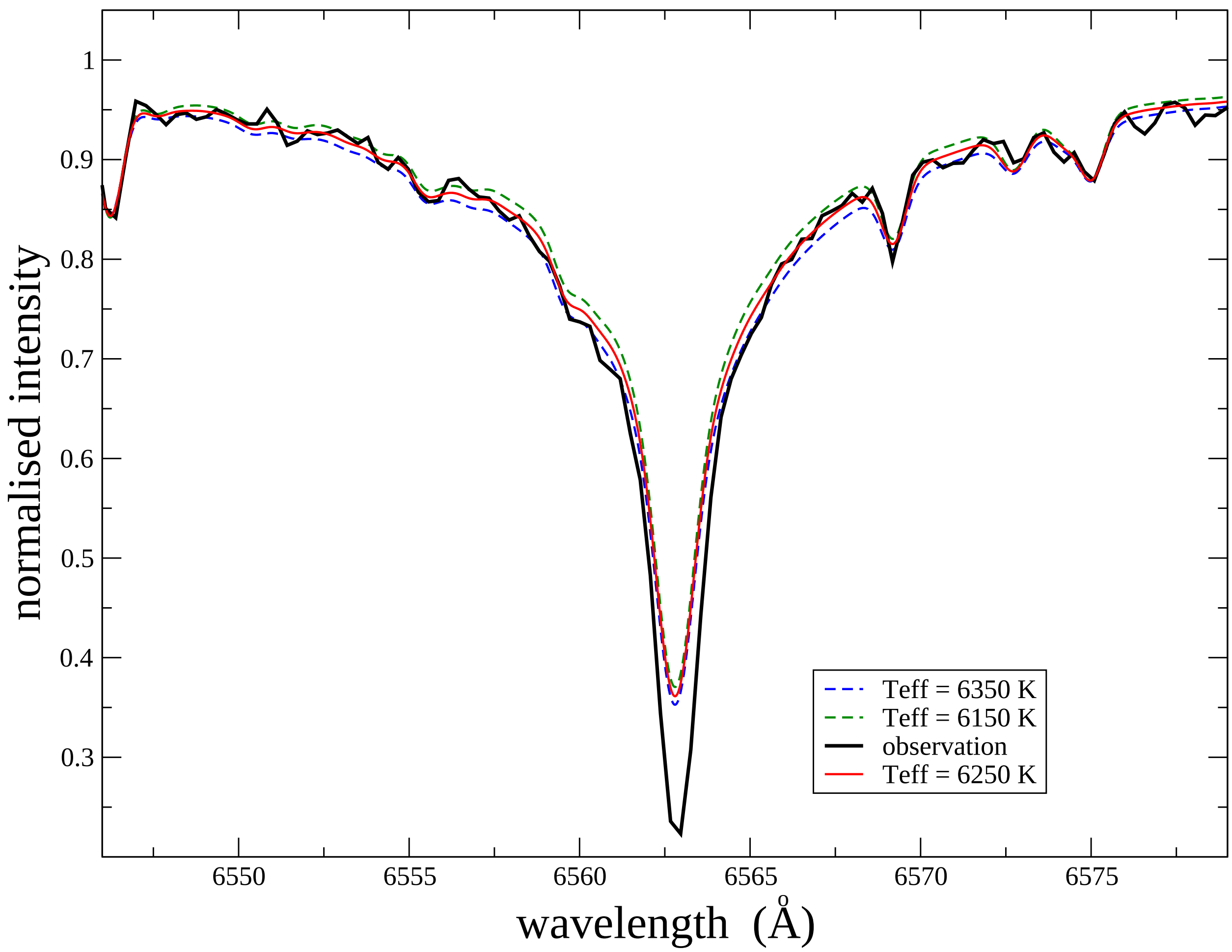

Fig. 1.— Comparison between the Hα line profile observed with the IDS spectrograph (black solid line) and synthetic profiles calculated with the final adopted $T_{\rm eff}$ of 6250 K (red solid line), and uncertainty (dashed lines).

obtaining the requested equilibrium for all of them. The number of lines adopted to measure the abundance-$\chi_{\rm excit}$ correlation for each ion is the same as the one we used to derive the final ion abundance, and it is listed in Table 2.

The surface gravity was derived from two independent methods based on (*i*) line profile fitting of gravity-sensitive metal lines with developed wings and (*ii*) ionisation balance for several elements. The first method is described in Fuhrmann et al. (1997) and uses the fact that the wings of the Mg I lines at λ 5167, 5172 and 5183 Å are very sensitive to $\log g$ variations. In practice we first derived the Mg abundance from other Mg I lines without developed wings, such as λ 5711 and 5785 Å, and then we fit the wings of the gravity indicator lines by tuning the $\log g$ value. To apply this method, very accurate $\log gf$ values and Van der Waals ($\log \gamma_{\rm Waals}$) damping constants are required for all the lines. We adopted the set of line parameters used by Ryabchikova et al. (2009) and included the uncertainty in these parameters in the uncertainty in $\log g$. We obtained a $\log g$ value of 4.2±0.2, in good agreement with Hebb et al. (2009). Our line profile fit of the Mg I lines with developed wings is shown in Fig. 3.

The second method, the ionisation equilibrium, is often used to derive the surface gravity, but this method is extremely sensitive to the non-LTE effects present for each ion/element, while Mg lines with developed wings (less sensitive to non-LTE effects) are more suitable as $\log g$ indicators (Zhao & Gehren 2000). For this reason we decided to keep the Mg lines as our primary $\log g$ indicator, and checked the result with the ionisation equilibrium. Adopting the $\log g$ value obtained from the analysis of the Mg I lines with developed wings and taking into account the abundance uncertainties, we satisfied the ionisation equilibrium for every element with two analysed ions.

Our main source for the atomic parameters of spectral lines is the VALD database with the default configuration. LTE abundance analysis was based on equivalent widths, analysed with a modified version (Tsymbal 1996) of the WIDTH9 code (Kurucz 1993a). For all analysed

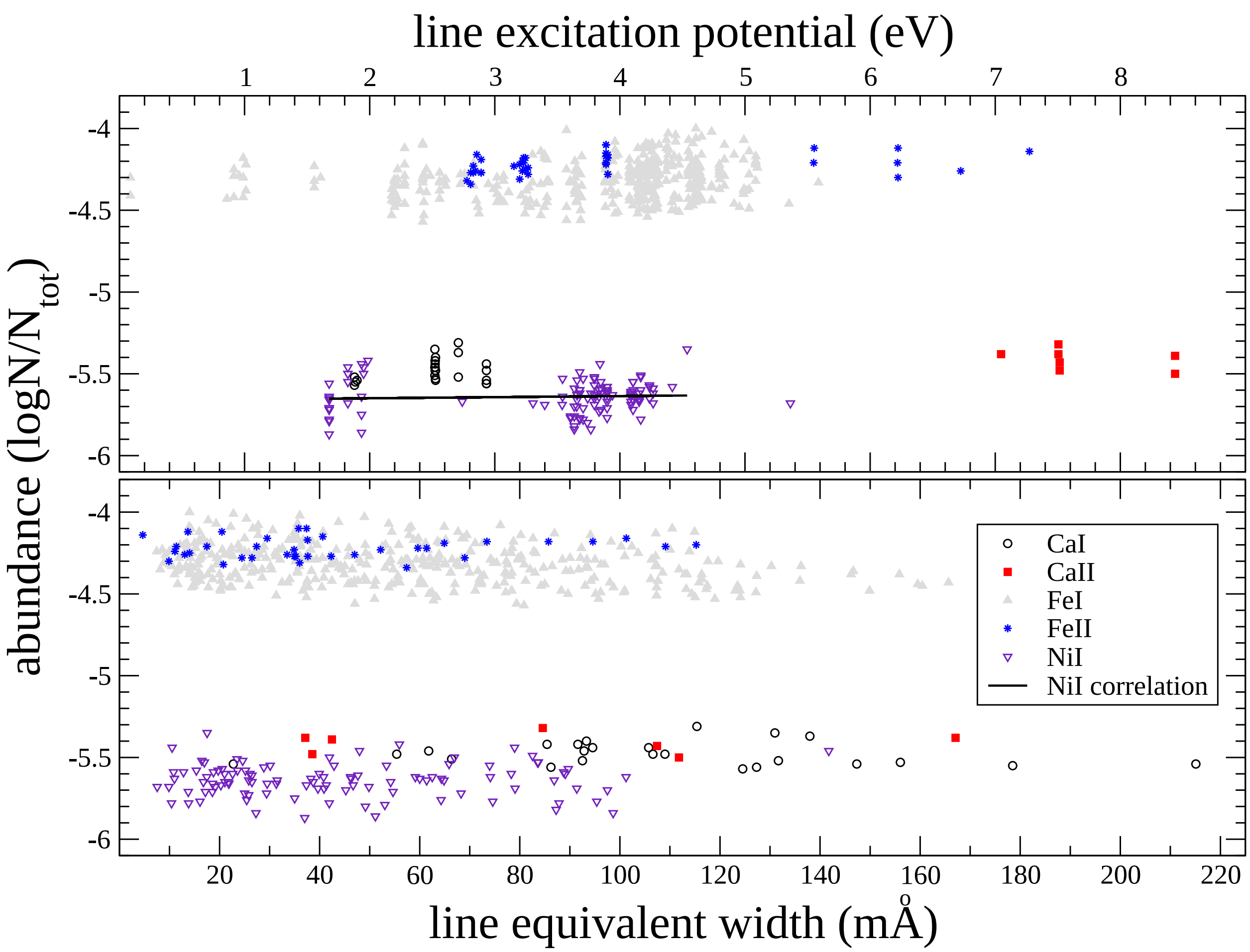

Fig. 2.— Top panel: abundance obtained for each measured line of Ca I (open circles), Ca II (filled squares), Fe I (filled triangles), Fe II (stars), and Ni I (open downside triangles) as a function of the line $\chi_{\rm excit}$. The black full line shows, as an example, the abundance-$\chi_{\rm excit}$ correlation for Ni I: 0.00637±0.01270, consistent with zero. Bottom panel: abundance obtained for each measured line of the ions given in the top panel, as a function of the measured line equivalent width. The effective temperature from metallic lines is derived eliminating the correlation shown in the top panel, while $\upsilon_{\rm mic}$ is determined eliminating the correlation shown in the bottom panel.

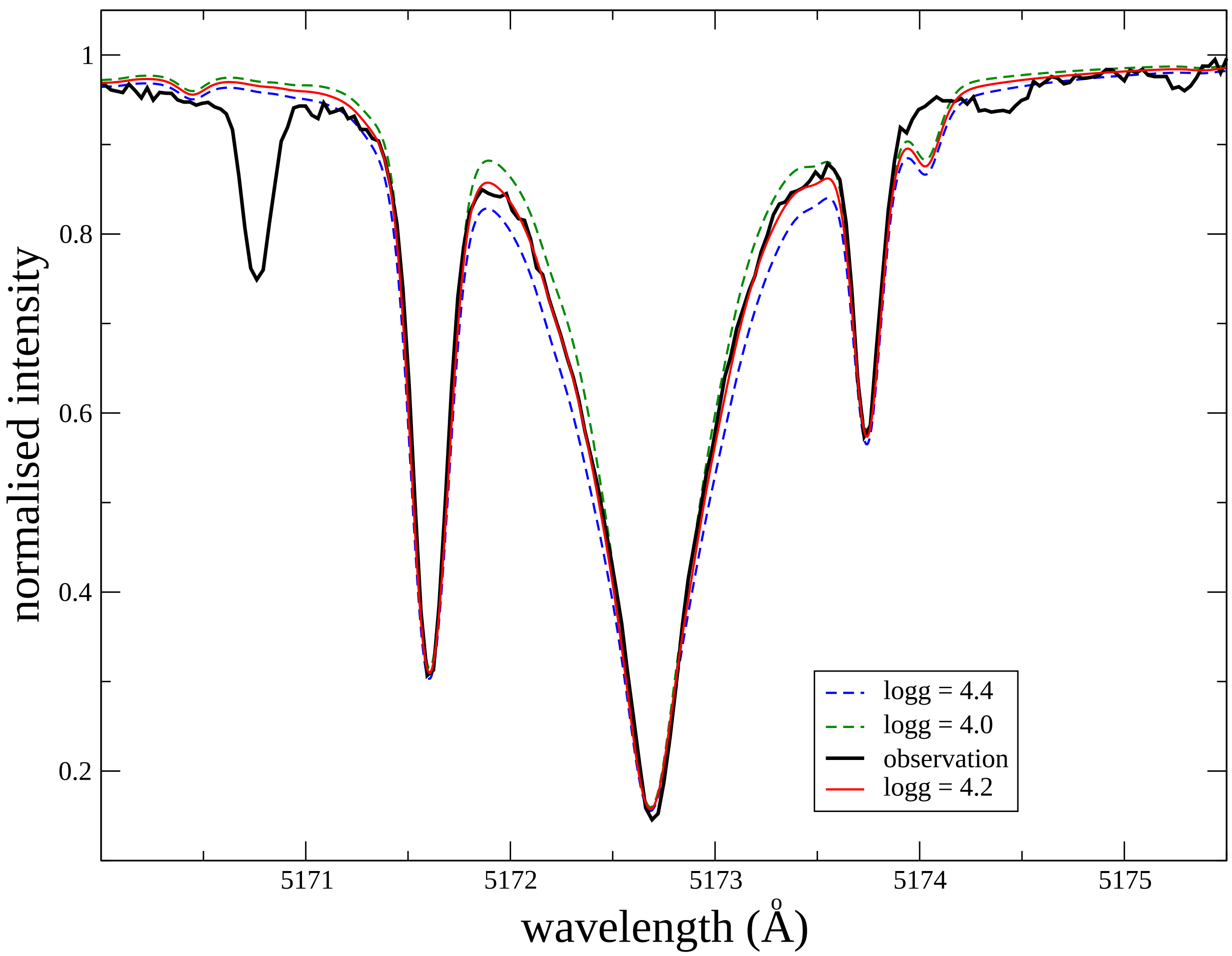

Fig. 3.— Comparison between the observed profile of the 5172 Å Mg I line (black solid line) and synthetic profiles calculated with the final adopted surface gravity of log g=4.2±0.2. We adopted the same combination of log gf and Van der Waals damping constants as in Ryabchikova et al. (2009): oscillator strengths from Aldenius et al. (2007) and damping constants from Fuhrmann et al. (1997).

elements/ions we used almost all unblended spectral lines with accurate atomic parameters available in the wavelength range 4240–9900 Å, except lines in spectral regions where the continuum normalisation was too uncertain. For blended lines, lines subjected to hyperfine splitting (*hfs*), lines situated in the wings of the hydrogen lines or for very shallow lines of specific ions we derived the line abundance by performing synthetic spectrum calculations with the SYNTH3 code. The *hfs* constants for abundance calculations were taken from Lawler et al. (2001b) for Eu II lines and from Smith et al. (1998) for the Li I line at λ 6707 Å. For the Barium abundance we used the Ba II lines at λ 5853.7 Å and 6496.9 Å for which we do not expect any relevant *hfs* effect (Mashonkina & Zhao 2006). A line-by-line abundance list with the equivalent width measurements, adopted oscillator strengths, and their sources is given in Table 1 (see the online material for the complete version of the table).

The microturbulence velocity was determined by minimising the correlation between equivalent width and abundance for several ions, as shown in Fig. 2 for Ca I, Ca II, Fe I, Fe II, and Ni I. To employ this method we used all ions for which the measured spectral lines covered a large range in equivalent width. In particular we took into account simultaneously: Si I, Ti I, Ti II, Cr I, Cr II, Mn I, and Y II, in addition to the ones present in Fig. 2. The final adopted $\upsilon_{\rm mic}$ is 1.2±0.3 km s^{-1}. The given error bar is the range of values resulting from minimisation of the correlation for each ion we considered.

The projected rotational velocity and macroturbulence ($\upsilon_{\rm macro}$) were determined by fitting synthetic spectra of several carefully selected lines to the observed spectrum. Given the $\upsilon \sin i$-$\upsilon_{\rm macro}$ degeneracy, we followed Valenti & Fisher (2005): we measured $\upsilon_{\rm macro}$ assuming $\upsilon \sin i$=0 km s^{-1} and then $\upsilon \sin i$ assuming $\upsilon_{\rm macro}$=4.75 km s^{-1} (from the $T_{\rm eff}$-$\upsilon_{\rm macro}$ relation published by Valenti & Fisher 2005). In the first case we obtained $\upsilon_{\rm macro}$=7.0±0.6 km s^{-1}, while in the second case we obtained $\upsilon \sin i$=4.6±0.5 km s^{-1}. In conclusion $\upsilon \sin i$ is in the range 0–4.6±0.5 km s^{-1}, while $\upsilon_{\rm macro}$ lays between 4.75 and 7.0±0.6 km s^{-1}. Only with a careful analysis

Table 1: Linelist of the lines used for the abundance analysis. The first and second columns list respectively the $\chi_{\rm excit}$ (in eV) and the log gf value for each line. Columns five and six list the equivalent width in mÅ and the abundance for each line, while the last column gives the reference for the log gf value. Spectral lines for which the abundance was measured with synthetic spectra, instead of equivalent widths, present an ”S” instead of the equivalent width value. Lines marked with ”*” are subject to hyperfine structure, discussed in detail in the main text, while lines marked with ”#” are multiplets (doublets or triplets) and in these cases we listed only the strongest line. The entire table can be viewed in the electronic version of the Journal.

Ion Wavelength Å	$\chi_{\rm excit}$ eV	log gf	EQW mÅ	abundance dex	Ref. log gf
Li I					
6707.7610*	0.000	-0.009	S	-9.47	SLN
C I					
5023.8389	7.946	-2.209	12.14	-3.49	WFD
5800.6016	7.946	-2.338	9.51	-3.43	WFD
6014.8300	8.643	-1.585	15.74	-3.40	WFD
6671.8450	8.851	-1.651	9.97	-3.36	WFD
7111.4694	8.640	-1.086	26.93	-3.55	WFD
7116.9879	8.647	-0.907	36.47	-3.52	WFD
...	...	...	...	...	...

SLN - Smith et al. (1998);

WFD - Wiese et al. (1996);

...

of the Rossiter-McLaughlin (RM) effect will it be possible to precisely measure $\upsilon \sin i$.

The final WASP-12 abundances, in $\log(N/N_{\rm tot})$, are given in Table 2 and the atmospheric abundance pattern is shown in Fig. 4 in comparison to the solar abundances (Asplund et al. 2005). While the large overabundance of K would disappear if non-LTE effects are taken into account (Takeda et al. 1996), the Sr overabundance is genuine since non-LTE effects are expected to be less then 0.05 dex for the Sr lines we analysed (Mashonkina et al. 2007, and references therein). In general we expect small non-LTE effects for WASP-12 due to the high stellar metallicity.

The stellar metallicity (Z) is defined as follows:

$$Z_{\rm star} = \frac{\sum_{a\geq 3} m_a 10^{\log(N_a/N_{tot})}}{\sum_{a\geq 1} m_a 10^{\log(N_a/N_{tot})}}, \tag{1}$$

where a is the atomic number of an element with atomic mass $m_{\rm a}$. Our abundances imply a metallicity of Z=0.021±0.002 dex, adopting the solar abundances by Asplund et al. (2005) for all the elements that we did not analyse.

The Z value adopted to characterise isochrones is calculated with the following approximation:

$$Z_{star} \simeq 10^{([Fe/H]_{star} - [Fe/H]_{\odot})} \cdot Z_{\odot} \ , \tag{2}$$

assuming $Z_{\odot}$=0.019 dex. We recalculated the Z of WASP-12 according to this approximation obtaining Z=0.036±0.002 dex.

4.1. Abundance uncertainties

The abundance uncertainties for each ion, shown in Table 2, are the standard deviations of the mean abundance obtained from the individual line abundances. Following Fossati et al. (2009), it is possible to conclude that in case of ions with a sufficiently high number of lines, the internal scatter for each ion includes the uncertainties due to equivalent width measurement and

Table 2: LTE atmospheric abundances of WASP-12 with error bar estimates based on the internal scatter from the number of analysed lines, *n*. The fourth column gives the WASP-12 abundances in dex relative to the solar values from Asplund et al. (2005). The last column gives the abundances of the solar atmosphere from Asplund et al. (2005). The Lithium and Europium abundances take hyperfine structure in the lines into account. The Gd II abundance is an upper limit. The symbol # indicates the ions for which the abundance was derived from line profile fitting, instead of equivalent widths.

Ion	WASP-12			Sun
	$\log(N/N_{\rm tot})$	n	$[N_{\rm el}/N_{\rm tot}]$	$\log(N/N_{\rm tot})$
LiI #	−9.47±0.05	2	+1.52	−10.99
CI	−3.45±0.08	14	+0.20	−3.65
NI #	−3.95	1	+0.31	−4.26
OI	−3.10	1	+0.28	−3.38
NaI	−5.63±0.04	4	+0.24	−5.87
MgI	−4.30±0.13	4	+0.21	−4.51
MgII	−4.29±0.05	3	+0.22	−4.51
AlI	−5.63±0.08	4	+0.04	−5.67
SiI	−4.47±0.18	60	+0.06	−4.53
SiII	−4.33±0.01	2	+0.20	−4.53
SI #	−4.78±0.05	8	+0.12	−4.90
KI	−6.12	1	+0.84	−6.96
CaI	−5.48±0.07	24	+0.25	−5.73
CaII	−5.41±0.06	7	+0.32	−5.73
ScII	−8.55±0.07	8	+0.44	−8.99
TiI	−6.95±0.09	37	+0.19	−7.14
TiII	−6.76±0.09	24	+0.38	−7.14
VI	−7.99±0.07	11	+0.05	−8.04
VII	−7.86±0.03	2	+0.18	−8.04
CrI	−6.17±0.06	32	+0.23	−6.40
CrII	−5.94±0.06	12	+0.46	−6.40
MnI	−6.41±0.16	16	+0.24	−6.65
FeI	−4.31±0.12	389	+0.28	−4.59
FeII	−4.22±0.06	38	+0.37	−4.59
CoI	−6.98±0.07	12	+0.14	−7.12
NiI	−5.64±0.10	105	+0.17	−5.81
CuI	−7.81±0.09	4	+0.02	−7.83
ZnI	−7.32	1	+0.12	−7.44
SrI #	−8.30	1	+0.82	−9.12
SrII#	−8.35±0.05	3	+0.77	−9.12
YII	−9.55±0.09	10	+0.28	−9.83
ZrII	−9.08	1	+0.37	−9.45
BaII	−9.37±0.06	2	+0.50	−9.87
LaII	−10.40	1	+0.51	−10.91
CeII	−10.29±0.07	3	+0.17	−10.46
NdII	−10.45±0.03	4	+0.14	−10.59
SmII	−10.64	1	+0.39	−11.03
EuII#	−11.30	1	+0.22	−11.52
GdII#	≤ −10.92	1	+0.00	−10.92
$T_{\rm eff}$	6250 K			5777 K
$\log g$	4.20			4.44

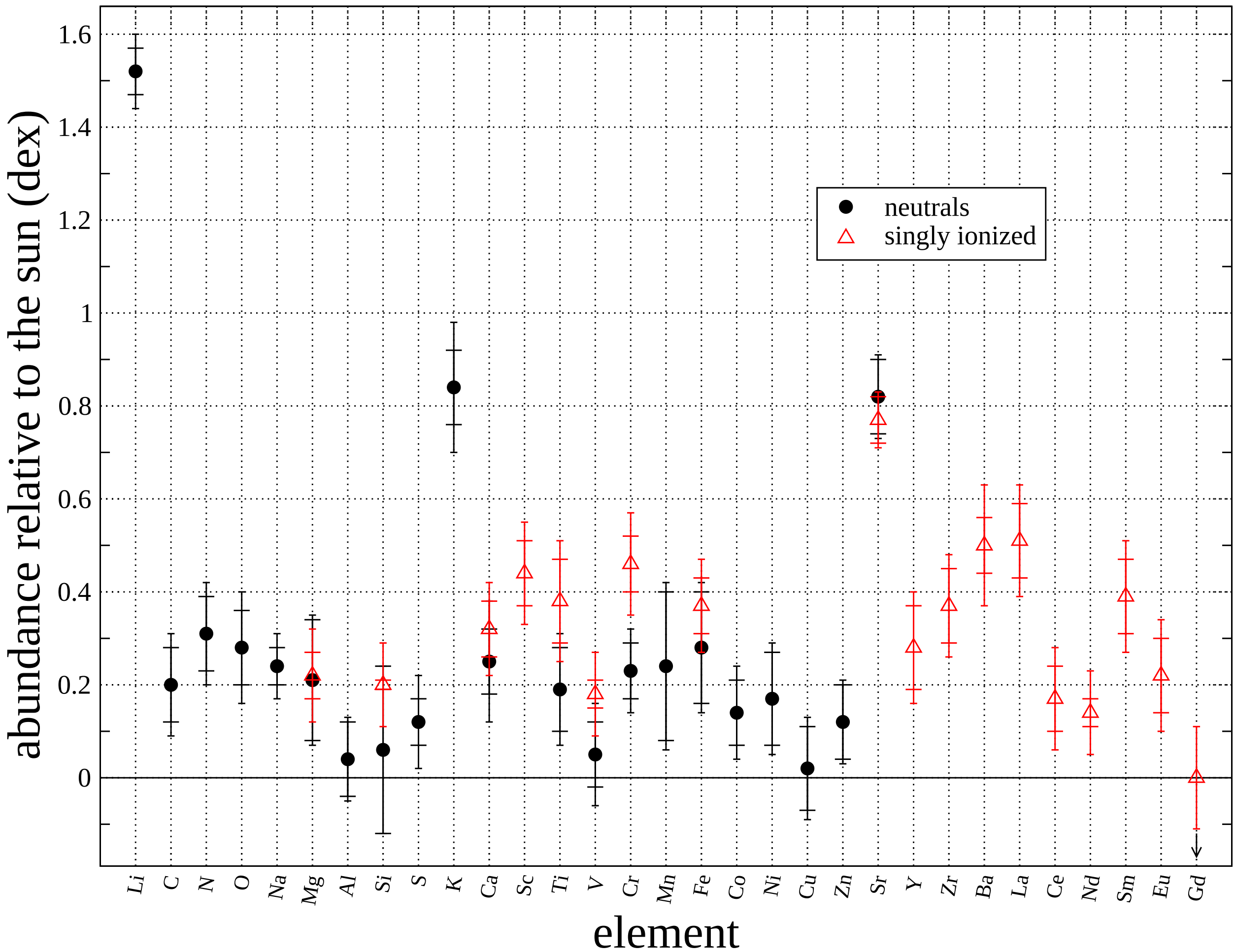

Fig. 4.— Ion abundance relative to the Sun (Asplund et al. 2005) of the WASP-12 atmosphere. Full points show the abundance of the neutral elements, while the open triangles show the abundance of the singly ionised elements. Each abundance value is shown with two uncertainty values: the standard deviation from the mean (column 3 of Table 3) and the total uncertainty (column eight of Table 3). We believe the real uncertainty lies between these two values.

continuum normalisation. In addition, from plotting the abundance scatter as a function of the number of lines, we can also infer an internal uncertainty of 0.08 dex, that can be applied as mean scatter when only one line of a certain ion is measured.

Table 3 shows the variation in abundance for each analysed ion, caused by the change of one fundamental parameter by $+1\sigma$, keeping fixed the other parameters.

Table 3 shows that the main source of uncertainty varies according to the element/ion (e.g. for the Fe-peak elements, neutrals are more sensitive to temperature variations, while ions are more sensitive to $\log g$ variations) and in some cases to the selected lines (e.g. the two Ba II lines selected to measure the Ba abundance are rather strong, therefore the Ba abundance is strongly dependent on $\upsilon_{\rm mic}$ variations).

Assuming the different uncertainties in the abundance determination are independent (though actually the systematic uncertainties will be correlated), we derived a pessimistic final error bar using standard error propagation theory, given in columns seven and eight of Table 3. Using the propagation theory we considered the situation where the determination of each fundamental parameter is an independent process. The mean value of the LTE uncertainties given in column eight of Table 3 is 0.11 dex. Due to the fact that for the parameter determination of both $T_{\rm eff}$, $\log g$ and $\upsilon_{\rm mic}$ we took into account all possible systematics (except non-LTE), we believe that the abundance uncertainties given in the last column of Table 3 can be considered as upper limits and that the real error bars lie between the values given in column three and eight of Table 3.

5. High precision magnetic field search

One of the main goals of our analysis is to search for a global stellar magnetic field in WASP-12. The ESPaDOnS spectropolarimeter yields high resolution and high SNR spectra of both Stokes I and V allowing this search. To detect the presence of a global magnetic field

Table 3: Uncertainty sources for the abundances of WASP-12. The third column shows the standard deviation $\sigma_{\rm abn}$ (scatt.) of the mean abundance obtained from different spectral lines (internal scattering); a blank means that only a single line was used, and we estimated the internal scattering to be 0.08 dex. Note that these values are identical to those given in Table 2. Columns 4, 5, and 6 give the variation in abundance estimated by increasing $T_{\rm eff}$ by 100 K, $\log g$ by 0.2 dex, and $\upsilon_{\rm mic}$ by 0.3 km s^{-1}, respectively. Column 7 gives the the mean error bar calculated adding the systematic uncertainties given in columns 4, 5 and 6 in quadrature i.e., $\sigma^2_{\rm abn}$ (syst.) = $\sigma^2_{\rm abn}$ ($T_{\rm eff}$) + $\sigma^2_{\rm abn}$ ($\log g$) + $\sigma^2_{\rm abn}$ ($\upsilon_{\rm mic}$). Column 8 gives the total mean error bar: $\sigma^2_{\rm abn}$ (tot.) = $\sigma^2_{\rm abn}$ (syst.) + $\sigma^2_{\rm abn}$ (scatt.).

Ion	abundance $\log(N/N_{\rm tot})$	$\sigma_{\rm abn}$ (scatt.) (dex)	$\sigma_{\rm abn}$ ($T_{\rm eff}$) (dex)	$\sigma_{\rm abn}$ ($\log g$) (dex)	$\sigma_{\rm abn}$ ($\upsilon_{\rm mic}$) (dex)	$\sigma_{\rm abn}$ (syst.) (dex)	$\sigma_{\rm abn}$ (tot.) (dex)
LiI	−9.47	0.05	0.06	−0.01	0.00	0.06	0.08
CI	−3.45	0.08	−0.05	0.05	0.00	0.07	0.11
NI	−3.95		−0.06	0.05	0.00	0.08	0.11
OI	−3.10		−0.08	0.05	0.00	0.09	0.12
NaI	−5.63	0.04	0.04	−0.04	−0.02	0.06	0.07
MgI	−4.30	0.13	0.04	−0.02	−0.02	0.05	0.14
MgII	−4.29	0.05	−0.08	0.04	−0.02	0.09	0.10
AlI	−5.63	0.08	0.03	−0.01	−0.01	0.03	0.09
SiI	−4.47	0.18	0.02	−0.01	−0.01	0.02	0.18
SiII	−4.33	0.01	−0.07	0.06	−0.02	0.09	0.09
SI	−4.78	0.05	0.06	−0.06	0.00	0.08	0.10
KI	−6.12		0.08	−0.08	−0.04	0.12	0.14
CaI	−5.48	0.07	0.07	−0.05	−0.06	0.10	0.13
CaII	−5.41	0.06	−0.06	0.04	−0.02	0.07	0.10
ScII	−8.55	0.07	0.01	0.07	−0.04	0.08	0.11
TiI	−6.95	0.09	0.08	0.00	−0.02	0.08	0.12
TiII	−6.76	0.09	0.00	0.07	−0.06	0.09	0.13
VI	−7.99	0.07	0.09	0.00	−0.01	0.09	0.11
VII	−7.86	0.03	0.00	0.08	−0.01	0.08	0.09
CrI	−6.17	0.06	0.06	−0.01	−0.02	0.06	0.09
CrII	−5.94	0.06	−0.02	0.08	−0.03	0.09	0.11
MnI	−6.41	0.16	0.07	0.00	−0.03	0.08	0.18
FeI	−4.31	0.12	0.06	−0.02	−0.04	0.07	0.14
FeII	−4.22	0.06	−0.02	0.07	−0.04	0.08	0.10
CoI	−6.98	0.07	0.07	0.00	−0.01	0.07	0.10
NiI	−5.64	0.10	0.06	−0.01	−0.03	0.07	0.12
CuI	−7.81	0.09	0.06	0.00	−0.02	0.06	0.11
ZnI	−7.32		0.02	0.02	−0.02	0.03	0.09
SrI	−8.30		0.02	−0.01	−0.03	0.04	0.09
SrII	−8.35	0.05	0.00	0.02	−0.02	0.03	0.06
YII	−9.55	0.09	0.01	0.08	−0.03	0.09	0.12
ZrII	−9.08		0.01	0.08	−0.01	0.08	0.11
BaII	−9.37	0.06	0.04	0.02	−0.11	0.12	0.13
LaII	−10.40		0.03	0.08	−0.01	0.09	0.12
CeII	−10.29	0.07	0.03	0.08	−0.01	0.09	0.11
NdII	−10.45	0.03	0.03	0.08	−0.01	0.09	0.09
SmII	−10.64		0.02	0.08	−0.02	0.08	0.12
EuII	−11.30		0.03	0.08	−0.01	0.09	0.12
GdII	≤ −10.92		0.02	0.08	0.00	0.08	0.11

and measure its strength we used the Least-Squares Deconvolution technique (hereafter LSD), adopting a code written by one of us (O. Kochukhov).

LSD is a cross-correlation technique developed for the detection and measurement of weak polarisation signatures in stellar spectral lines. The method is described in detail by Donati et al. (1997) and Wade et al. (2000). We decided to use the LSD approach to detect a magnetic field in WASP-12 since this method is the most precise currently available, especially for stars with rich line spectra and low projected rotational velocity ($\upsilon \sin i$), such as WASP-12.

We applied the LSD technique to the Stokes V spectra from each of the two nights using about 6 450 atomic spectral lines with the only cut-off criterion based on the calculated line depth (>10%), and in both cases no magnetic field was found. From the spectrum of January 3rd we obtained $\langle B_z \rangle = 2.3 \pm 5.3$ G, with a SNR of the Stokes V LSD profile of 2400, while from the second night spectrum we obtained $\langle B_z \rangle = -10.1 \pm 4.2$ G, with a SNR of the Stokes V LSD profile of 3380. We obtained similar values also from both null profiles. Figure 5 shows the LSD profiles.

In late-type stars, the stellar magnetic field is directly connected to the chromospheric activity, that can be monitored with the Ca II H and K lines. In Fig. 6 we compare the profiles of the Ca II H and K lines, observed with ESPaDOnS, with the mean line profiles of τ Boo (Shkolnik et al. 2005) obtained averaging several CFHT spectra acquired with the GECKO spectrograph[4]. This comparison is particularly valuable because both stars are planet hosting and have similar fundamental parameters and age (Gonzalez et al. 2010a), where the difference is mainly in the $\upsilon \sin i$ values (τ Boo has a $\upsilon \sin i$ of about 13.5 km s^{-1}). Figure 6 does not show the presence of any anomaly in WASP-12 Ca II H and K line cores. Knutson et al. (2010) determined the $\log(R'_{HK})$ chromospheric stellar acitvity parameter in a set of planet hosting stars, reporting for WASP-12

[4] *http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Gecko/*

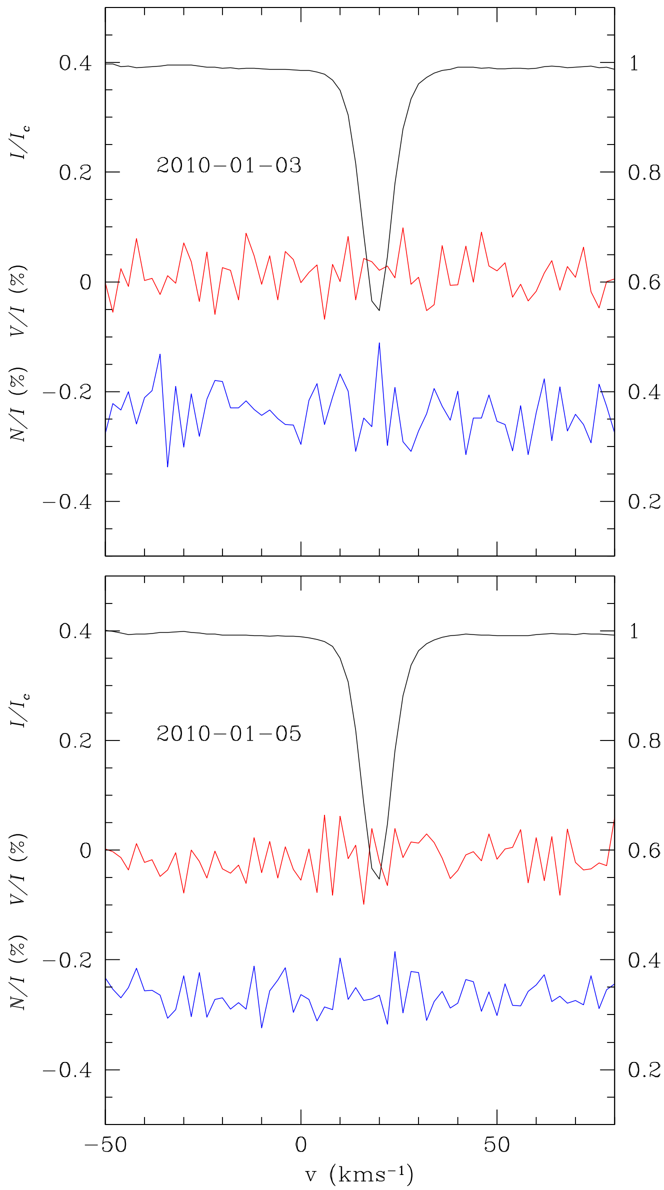

Fig. 5.— LSD profiles from the spectra obtained on January 3rd (top panel), corresponding to an orbital phase of 0.80, and January 5th 2010 (bottom panel), corresponding to an orbital phase of 0.81. In each panel, the top black line shows Stokes I, normalised to the continuum (the corresponding units are given in the right y-axis). The middle red line corresponds to the V/I profile and the bottom blue line to the null profile (Donati et al. 1997); their corresponding units are given in the left y-axis. The Stokes I LSD profile is centered on the stellar radial velocity and the null profile is shifted downward by an arbitrary offset.

the remarkably low value of -5.500, the lowest in their sample.

The bottom panel of Figure 1 in Fossati et al. (2010) shows the core of the Mg II UV resonance lines (further stellar activity indicators) of WASP-12 and here the lack of any line core emission is clear, in agreement with the low level of stellar activity reported by Knutson et al. (2010).

It is well known that the chromospheric activity is strongly correlated with the stellar rotational velocity, that for WASP-12 is unknown. Given the very small RM effect shown by Husnoo et al. (2010), it is probable that the low stellar activity of WASP-12 might be connected to a low rotational velocity. It is also possible that the star is either passing through a period of low activity, or WASP-12 is much older than reported by Hebb et al. (2009) (more than 1 Gyr older), or the typical signs of stellar activity, such as emission in the cores of the Mg II resonance lines, are absorbed by the material lost by the planet and falling onto the star (see Li et al. 2010; Fossati et al. 2010). A more thorough analysis and discussion of the stellar activity and of the reasons behind its low level will be given in a following work, now in preparation.

6. Discussion

6.1. Atmospheric parameters and convection

Because WASP-12 has a relatively low effective temperature, its hydrogen lines are ideal indicators of atmospheric T-P structure. Generally, fitting hydrogen line profiles, rather than any other atomic line, provides an accurate estimate of $T_{\rm eff}$. On the other hand, at low temperatures, convection becomes an important energy transfer mechanism, influencing the photospheric temperature stratification and, thus, hydrogen line formation. The derived value of $T_{\rm eff}$ then depends on the convection treatment used in the model atmosphere calculations.

There are basically two formalisms of convection treatment available for model atmosphere

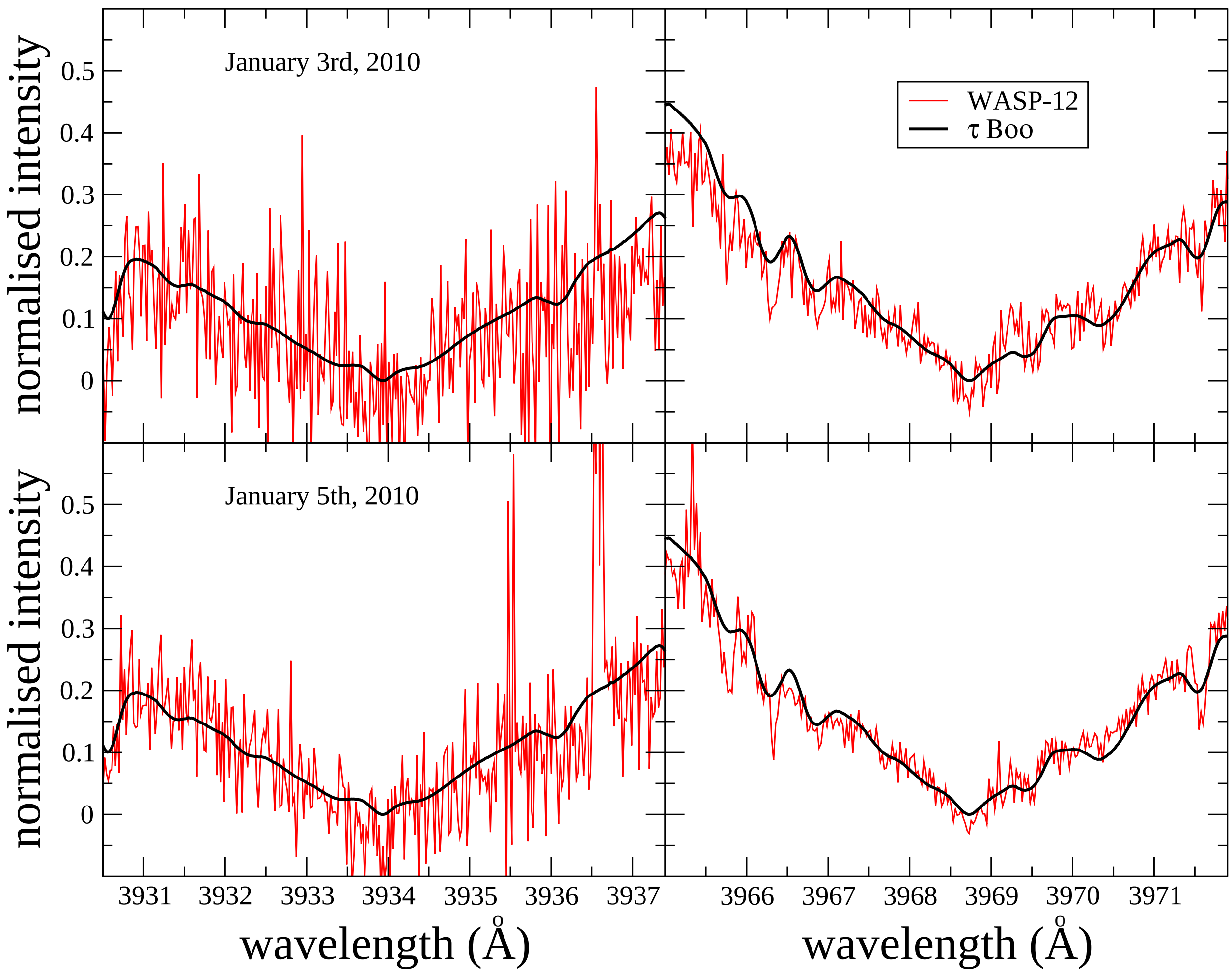

Fig. 6.— Comparison of the observed Ca K and H line (left and right panels, respectively) profiles between WASP-12 (thin line) and the planet hosting star τ Boo (thick line, Shkolnik et al. 2005). The two upper panels show the WASP-12 spectrum obtained on January 3rd, 2010, while the two lower panels show the spectrum obtained on January 5th, 2010.

computations: the well known mixing-length theory (MLT) (Böhm-Vitense 1958), which relies on some free parameter (α), describing the characteristic length traveled by convective cells before they disappear, and further improvement of stellar convection developed by Canuto & Mazzitelli (1991, CM hereafter). The main advantage of the new model is that it does not require any adjustable parameters like α, which is now computed based on the geometrical depth scale inside the convective zone. It also accounts for the full spectrum of turbulent eddies, and is therefore superior to the single-eddy assumption made by MLT. More details can be found in Canuto & Mazzitelli (1992).

Physically the CM convection model is somewhat superior to MLT, therefore we preferred CM convection over MLT in our analysis. In the case of WASP-12, we find no critical differences in Hα profiles using both CM and MLT convection theories with the commonly accepted $\alpha = 1.25$. This is because the wings of Hα are formed mainly in the region right above the photosphere where convection plays a less important role in the energy balance. However, bluer Balmer lines are formed deeper and thus can show the changes in the temperature stratification introduced by convection. For instance, this is the case for the Hγ line for which MLT predicts weaker line wings (i.e. stronger convective energy transport): one needs an approximately 100 K hotter model to fit the Hγ line wings with MLT convection. However, it is then clear that only CM allows a consistent fit simultaneously for Hα and Hγ lines with the same $T_{\rm eff}$.

6.2. The distance and age of WASP-12

The basic parameters of WASP-12 were derived by Hebb et al. (2009). $T_{\rm eff}$, $\log g$, metallicity, and $\upsilon \sin i$ were derived from the observed stellar spectrum using spectral synthesis; a simultaneous Markov chain Monte Carlo (MCMC) fit to radial velocity and transit light curve measurements produced values for $R_{\rm P}/R_*$, R_*, M_* and the orbital semi-major axis a. The observed spectral type of the star and its radius imply the luminosity and the spectral energy distribution. Using this information, the 2MASS IR fluxes can be used to derive the distance (IRFM; Blackwell et al. 1979). This method yields a distance to WASP-12 of 265±20 pc (`http://www.superwasp.org/wasp_planets.htm`), assuming a typical main-sequence stellar radius; and 385±30 pc, assuming the stellar radius from the MCMC fits of Hebb et al. (2009) (B. Smalley, priv.comm.). We note that the IRFM implicitly assumes solar metallicity and zero reddening, both inapplicable for WASP-12. Since the orbital period and the radial velocity amplitude fix the value of a, and the transit light curve fixes the ratio a:R_*, the stellar distance of 385±30 pc is to be preferred. Hebb et al. (2009) also estimated the age of WASP-12 by fitting isochrones to the position of WASP-12 in a modified HR diagram (temperature vs. inverse cube root of the stellar density), obtaining an age of $2.0^{+0.5}_{-0.8}$ Gyr old; given the several uncertainties, they increased the error bars to 1 Gyr, concluding that WASP-12 is 2±1 Gyr old.

One of the most secure empirical properties of the star is its colour, or equivalently effective temperature. We can assess the distance and age of WASP-12 by comparing the effective temperature with isochrones and evolutionary tracks. Figure 7 shows four isochrones from Marigo et al. (2008) with a metallicity Z of 0.030, the maximum available value of Z, adopted following Eq. 2. WASP-12's effective temperature places it on the vertical thick blue line of Fig. 7, where the other two full vertical blue lines are defined by the uncertainty on $T_{\rm eff}$. On this central line we placed three points, which correspond to distances of 265 pc (lower point), 295 pc (middle point) and 465 pc (upper point). The lower point lies well below the zero-age main sequence (ZAMS). From this we can rule out a distance as close as 265 pc; this concurs with the MCMC fitting of Hebb et al. (2009) in implying the star is bigger than the typical main sequence stellar radius.

We can see that a range of possible ages and distances are compatible with the isochrones. In the region of Fig. 7 between the two solid triangles, several isochrones are consistent with the empirical effective temperature. The 2.65 Gyr isochrone is just consistent with the lower limit on WASP-12's effective temperature: the loop to the right at the main sequence turn-off point of

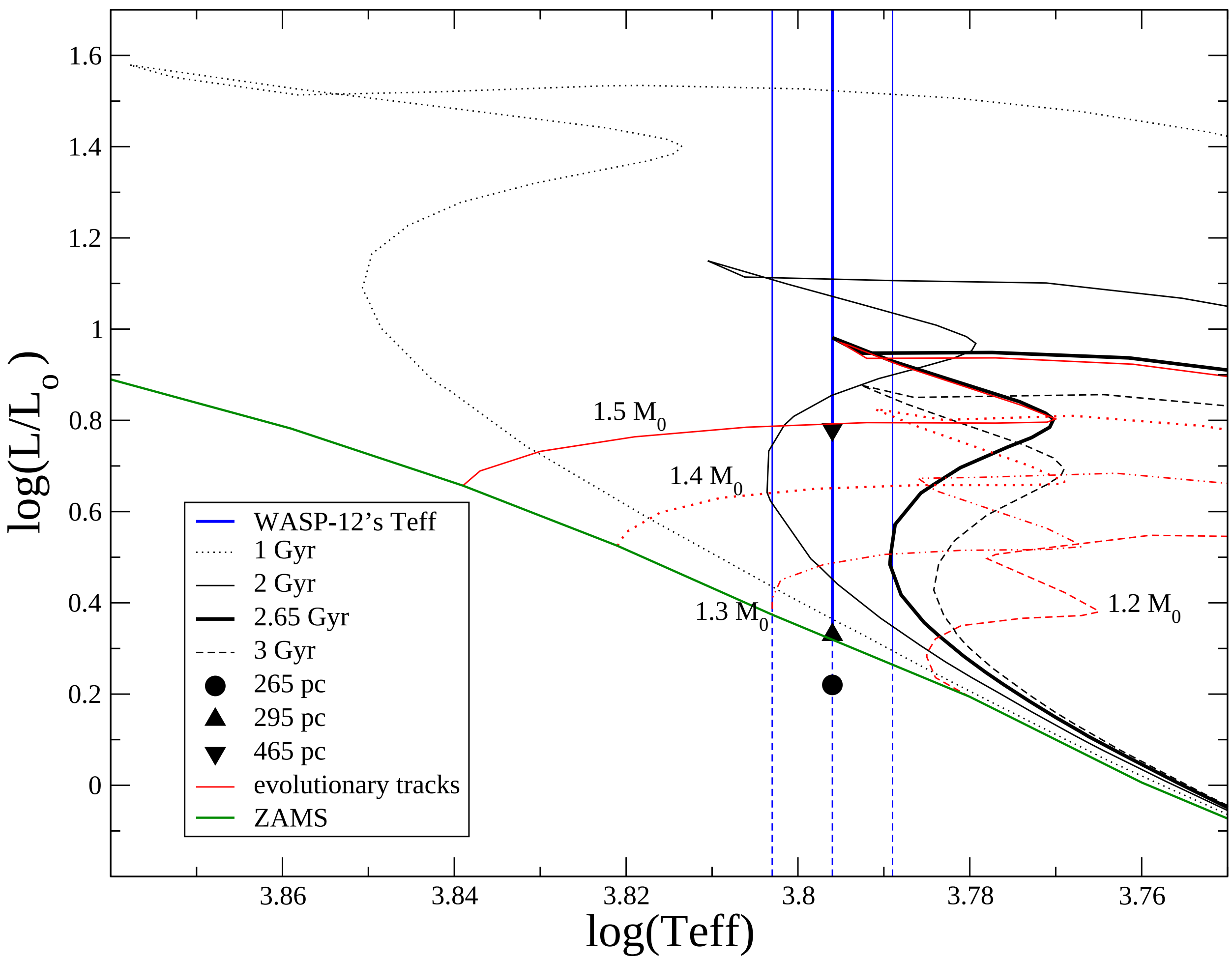

Fig. 7.— Position of WASP-12 on the HR diagram assuming three different stellar distances: 265 pc (circle), 295 pc (triangle), and 465 pc (inverted triangle). The maximum and minimum distances were calculated adopting $T_{\rm eff}$=6250 K and interstellar reddenings from (Amôres & Lépine 2005). The dotted, thin full and dashed lines show isochrones from Marigo et al. (2008) corresponding to ages of 1 Gyr, 2 Gyr and 3 Gyr, respectively, encompassing the possible age range of WASP-12 from Hebb et al. (2009). The thick full line is the 2.65 Gyr isochrone we argue this is the maximum possible age for WASP-12. The red lines show evolutionary tracks from Girardi et al. (2000) for 1.5 $M/M_{\odot}$, 1.4 $M/M_{\odot}$, 1.3 $M/M_{\odot}$and 1.2 $M/M_{\odot}$, from top to bottom. Both isochrones and evolutionary tracks assume a metallicity Z of 0.03. The blue vertical lines show the WASP-12's temperature range; these lines change from full to dashed below the ZAMS, indicated by the green line.

this isochrone intersects the lower limit on the temperature. No star of this age is consistent with WASP-12's colour except for those which are turning on to the horizontal branch, higher up in the diagram at $\log L/L_{\odot} \approx 1$. For stars at this stage of evolution $\log g \approx 3.8$, whereas the spectrum of WASP-12 implies $\log g \approx 4.2$ (c.f. Sect 4). WASP-12 thus cannot be turning on to the horizontal branch. Consequently we can constrain the position of WASP-12 in Fig. 7 to be around or younger than the main sequence turn-off.

Applying this reasoning, the oldest possible age for WASP-12 is 2.65 Gyr. This arises from the intersection of lower limit on WASP-12's effective temperature and the full thick isochrone in Fig. 7. For all isochrones younger than this, there is also an intersection at or before the main-sequence turn-off. For the isochrones older than this no allowed intersection occurs: only evolved stars have compatible temperatures, but these are ruled out by their surface gravity.

The full red lines in Fig. 7 are evolutionary tracks, from Girardi et al. (2000), for stars of mass 1.2 $M/M_{\odot}$, 1.3 $M/M_{\odot}$, 1.4 $M/M_{\odot}$ and 1.5 $M/M_{\odot}$ respectively from bottom to top. WASP-12 is clearly hotter than a 1.2 $M/M_{\odot}$ star for any age, therefore we conclude its mass exceeds 1.2 $M/M_{\odot}$. Interpolating between the evolutionary tracks, we estimate a limit on the mass of WASP-12 of around 1.23 $M/M_{\odot}$. This is consistent with MCMC fitting of Hebb et al. (2009), but is a tighter constraint.

The evolutionary track for 1.3 $M/M_{\odot}$ almost exactly coincides with the intersection of the 2.65 Gyr isochrone with the lower limit on the effective temperature. The oldest possible age therefore corresponds to a stellar mass of about 1.3 $M/M_{\odot}$. For higher masses, the empirical effective temperature intersects the evolutionary track while the star is still on the main sequence, and is therefore consistent with WASP-12's $\log g$. The 1.4 $M/M_{\odot}$ evolutionary track is consistent with the empirical effective temperature, and is also consistent with the MCMC fitting of Hebb et al. (2009).

The upper limit on the mass from Hebb et al. (2009) is just below 1.5 $M/M_{\odot}$. We can use this to infer an upper limit on the luminosity, and hence the distance. We find that the maximum distance is 465 pc. On the other hand, the minimum distance is obtained at the intersection of the vertical line that defines WASP-12's effective temperature and the ZAMS; this distance is 295 pc. These distances are computed taking into account insterstellar reddenings as given by (Amôres & Lépine 2005).

One effective way to measure the age of a late-type star is the comparison of the lithium abundance with that of open cluster member stars for which the age is precisely known. For a more thorough analysis of the Li I line at λ 6707 Å we downloaded from the SOPHIE archive[5] all the 21 mid-resolution spectra[6] (R∼40 000) of WASP-12 obtained for the radial velocity analysis published by Hebb et al. (2009).

Figure 8 shows a comparison between the 21 SOPHIE spectra and synthetic spectra calculated with the adopted stellar parameters and abundances around the region of the Li I line at λ 6707 Å; the bottom-right panel shows the same comparison, but with the ESPaDOnS spectrum. This plot shows that the Li abundance derived from the ESPaDOnS spectrum fits the SOPHIE data as well and that there is no line profile variation of the Li line with the orbital phase. We measured also the equivalent width of the Li line in each of these spectra and we did not find any significant time variation. For this reason we believe that the lack of detection of this Li I line in the SARG spectrum of WASP-12, reported by Hebb et al. (2009), could be due to the low SNR or to a wrong line identification.

From a comparison between the lithium abundance of WASP-12 and the results published by Sestito & Randich (2005) we can only conclude that WASP-12 is older than 500 Myr, which

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[5]http://atlas.obs-hp.fr/sophie/

[6]SOPHIE is a cross-dispersed échelle spectrograph mounted at the 1.93-m telescope at the Observatoire de Haute-Provence (OHP).

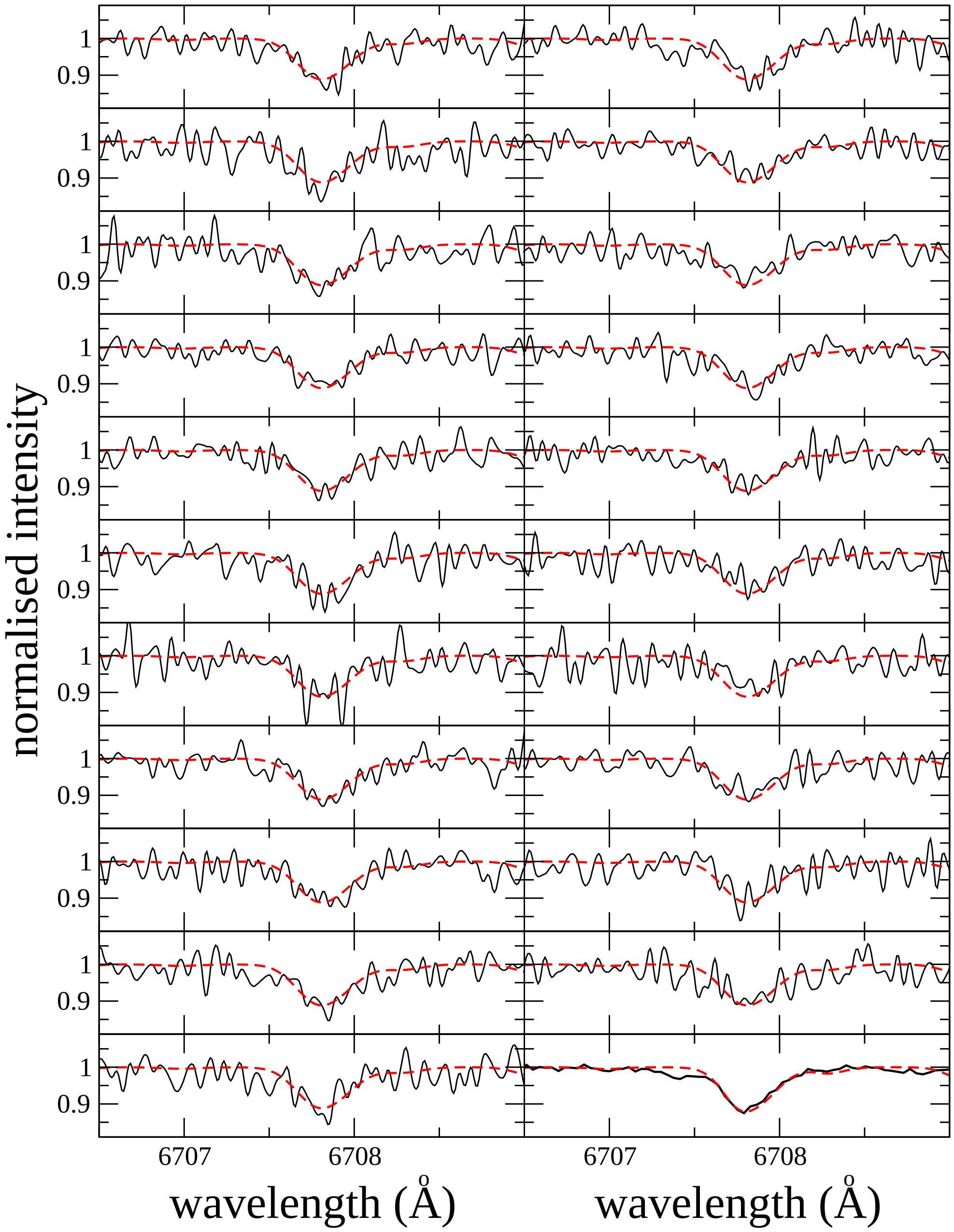

Fig. 8.— Comparison between the observed phase dependent SOPHIE spectra (black solid line) of WASP-12 around the Li I line at λ 6707 Å and synthetic spectra (dashed red line) calculated with the Li abundance and the parameters obtained from the analysis of the ESPaDOnS data. The bottom-right panel shows the same comparison, but with the analysed ESPaDOnS spectrum instead. The synthetic spectra take into account the difference in resolution between SOPHIE and ESPaDOnS.

is in agreement with the 2.0±1.0 Gyr given by evolutionary tracks (Hebb et al. 2009). The large uncertainty is caused by the extremely slow lithium depletion for stars with effective temperatures similar to that of WASP-12, due to the shallow surface convection zone.

In conclusion our analysis on the age of WASP-12 leads to a stellar age between 1.0 Gyr (lower limit given by Hebb et al. 2009) and 2.65 Gyr (from the analysis of the HR diagram), as shown also in Table 4 that lists the minimum and maximum values we obtained for the stellar age, mass and distance.

Table 4: Minimum and maximum values of WASP-12's age (in Gyr), $M/M_{\odot}$ and distance (in pc) as derived by the analysis of the HR diagram. The values marked with an "*" are taken from Hebb et al. (2009).

Parameter	Minimum value	Maximum value
age (Gyr)	1.0*	2.65
$M/M_{\odot}$	1.23	1.49*
distance (pc)	295	465

6.3. Is WASP-12 a chemically peculiar star?

One of the main purpose of this work is to search for chemical peculiarities that could be connected with pollution of the stellar atmosphere by material lost by the planet. This can be done in different ways, as also shown in the extensive salient literature present (see e.g. Neves et al. 2009, and references therein). WASP-12 is a promising target for signs of atmospheric pollution: WASP-12 b is most likely currently losing material (Fossati et al. 2010); this material is believed to be forming a circumstellar disk that is accreting onto the star, polluting the stellar photosphere

(Li et al. 2010). Classical ways of looking for atmospheric pollution are by searching: (*i*) chemical peculiarities of single elements, such as Li and Be (e.g. Israelian et al. 2004); (*ii*) a trend in the element abundance against the condensation temperature (T_c; see e.g. Sadakane et al. 2002; Ecuvillon et al. 2006; Meléndez et al. 2009); (*iii*) chemical peculiarities of the abundance pattern in comparison to reference stars (both planet hosting and non-planet hosting).

When searching for small effects on the stellar atmospheric abundances it is important to determine whether a certain star belongs to the thin or thick Galactic disk population. To do so we performed both a kinematic and chemical analysis of WASP-12. We calculated the Galactic velocity vectors (U, V, W) corrected to the local standard of rest (LSR) using the formalism of Johnson & Soderblom (1987), instead defining U as positive towards the Galactic anti-centre. As done by Sozzetti et al. (2006), WASP-12 was then placed on the Toomre diagram of the Soubiran & Girard (2005) stellar sample, indicating that WASP-12 has a peculiar velocity less than 85 km s^{-1}, strongly indicative of thin disk membership. From the WASP-12 abundances, we then compared our values of [α/Fe] (−0.15 dex) and [Fe/H] (+0.28 dex), where [α/Fe] is defined as 0.25([Mg/Fe]+[Si/Fe]+[Ca/Fe]+[Ti/Fe]), with the Soubiran & Girard (2005) sample, obtaining that WASP-12 is again consistent with the properties of the thin disk population.

In our analysis we are not able to look for chemical peculiarities of both Li and Be. As shown in Fig. 8, our spectra do not have the SNR and the resolution necessary to perform a precise analysis of the Li^6/Li^7 ratio, but we can compare the lithium abundance obtained for WASP-12 with that of other planet hosting stars. Israelian et al. (2004) and Gonzalez et al. (2010a) published lithium abundances of stars hosting a giant planet or a brown dwarf and compared them to a set of non-planet hosting stars. The lithium abundance we obtained for WASP-12 matches that of both set of stars, showing clearly that Li is not peculiar in WASP-12. Our spectra do not include the region around λ 3130 Å covering the two Be II lines usually adopted to measure the Be abundance.

6.3.1. *Volatile vs. refractory elements*

An effective way to check whether a stellar photosphere is polluted by accretion of metal-rich material is to examine the correlation between the relative abundance of various elements and their T_c. In accreting metal-rich material the refractory elements tend to form dust grains that are blown away by the stellar wind. Thus the star accretes more volatile than refractory elements, as happens, for example, in λ Bootis stars (Martínez-Galarza et al. 2009). Our WASP-12 ion abundance are shown against condensation temperature (taken from Lodders 2003) in Fig. 9.

The correlation obtained between the ion abundances relative to the Sun (Asplund et al. 2005) and T_c is not statistically significant: $6.91 \pm 5.64 \times 10^{-5}$. In the past years several authors (e.g. Sadakane et al. 2002; Ecuvillon et al. 2006; Sozzetti et al. 2006) looked for the same kind of correlation in several planet hosting stars, without having found any. The trend we obtain for WASP-12 is also indicative of a null result.

Meléndez et al. (2009), applying a differential analysis on the Sun and solar twins, discovered that the Sun shows a highly significant correlation of the abundances (relative to the mean abundance of the solar twins) in respect to the condensation temperature. In addition this correlation shows a significant break at $T_c \sim 1200$ K. Meléndez et al. (2009) and Gonzalez et al. (2010b) came to the conclusion that this correlation is likely connected to the presence of planets around the Sun. The detection of this kind of correlation requires very high precision abundances (error bars < 0.05 dex and free from systematic differences), attainable only with a differential analysis. The application of this method to WASP-12 would require observations of stars that can be considered twins of WASP-12 (similar $T_{\rm eff}$, metallicity, age, and population). The choice of the WASP-12 twins will be of crucial importance because effects such as diffusion, more prevalent for F-type stars than G-type stars, are strongly age and $T_{\rm eff}$ dependent, and consequently could easily hide or mimic pollution signatures.

Our analysis does not lead to a firm conclusion about the atmospheric pollution of WASP-12.

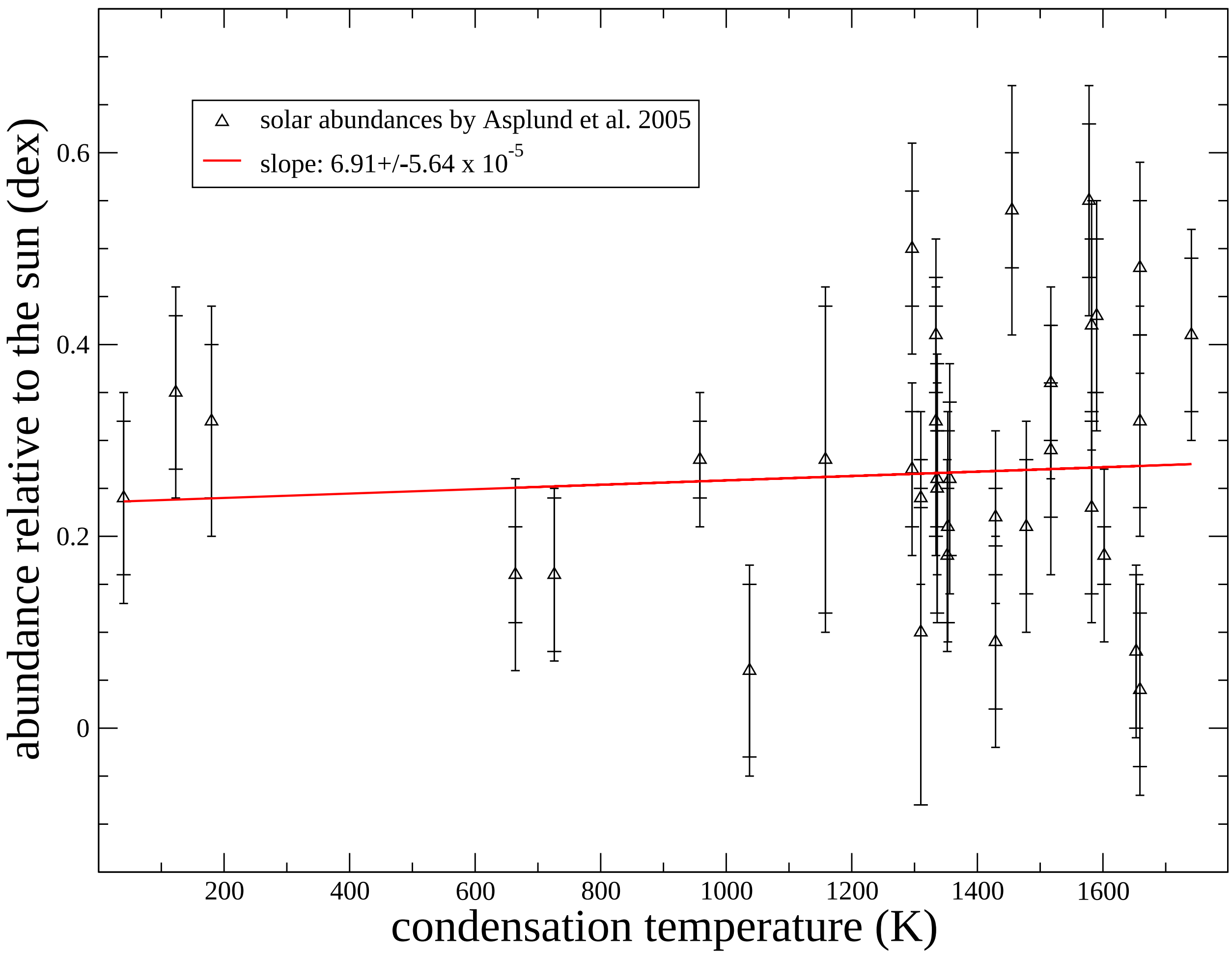

Fig. 9.— Ion abundance relative to the sun (Asplund et al. 2005) as a function of the condensation temperature. The full line shows the linear fit to the data. The abundance uncertainties are given as in Fig. 4.

6.3.2. *Comparison with previous analysis*

To check whether WASP-12 has a peculiar abundance pattern we compared the abundances with those obtained by other authors on a large number of stars with a similar $T_{\rm eff}$. In particular we took into account the results of the abundance analysis on stars that are not known planet hosts, in the temperature range 6000–6500 K, and with a [Fe/H]>0.0 dex. We decided to use such a small temperature range to decrease the effect of possible systematics, such as non-LTE effects. In addition, since we are interested in looking for a peculiar pattern, we decided to use only the stars with an over-solar iron abundance and to subdivide the sample of comparison stars according to their iron abundance: 0.0<[Fe/H]≤0.1, 0.1<[Fe/H]≤0.2, and [Fe/H]>0.2. To have a better statistical view of each subsample we decided to plot in our comparisons not only the mean abundance and relative standard deviation for the comparison stars, but also their abundance range. To accomplish all these requirements, we needed to have a large set of non-planet hosting stars, such as the one provided by Valenti & Fisher (2005).

Valenti & Fisher (2005) performed a parameter determination and LTE abundance analysis of more than 1000 late-type main sequence stars. For each star they derived the abundances of Na, Si, Ti, Fe, and Ni. This sample provided us with comparison abundances for 59 stars with 0.0<[Fe/H]≤0.1 dex, 36 stars with 0.1<[Fe/H]≤0.2 dex, and 22 stars with [Fe/H]>0.2 dex. The comparison between our WASP-12 abundances and the ones from the sample of Valenti & Fisher (2005) is shown in Fig. 10.

Figure 10 shows that the abundances of Ti and Fe are clearly comparable to the ones of the higher metallicity subsample, as expected given the fact that [Fe/H] of WASP-12 is about 0.3. The Na abundance of WASP-12 falls within the abundance range of the high-metallicity stars of the comparison sample, due to the large range covered by the Na abundance, while Ni shows a mean abundance that is just outside the abundance range. The Si abundance looks definitely more similar to the one of the set of stars with 0.1<[Fe/H]≤0.2 dex, but the large uncertainty on this

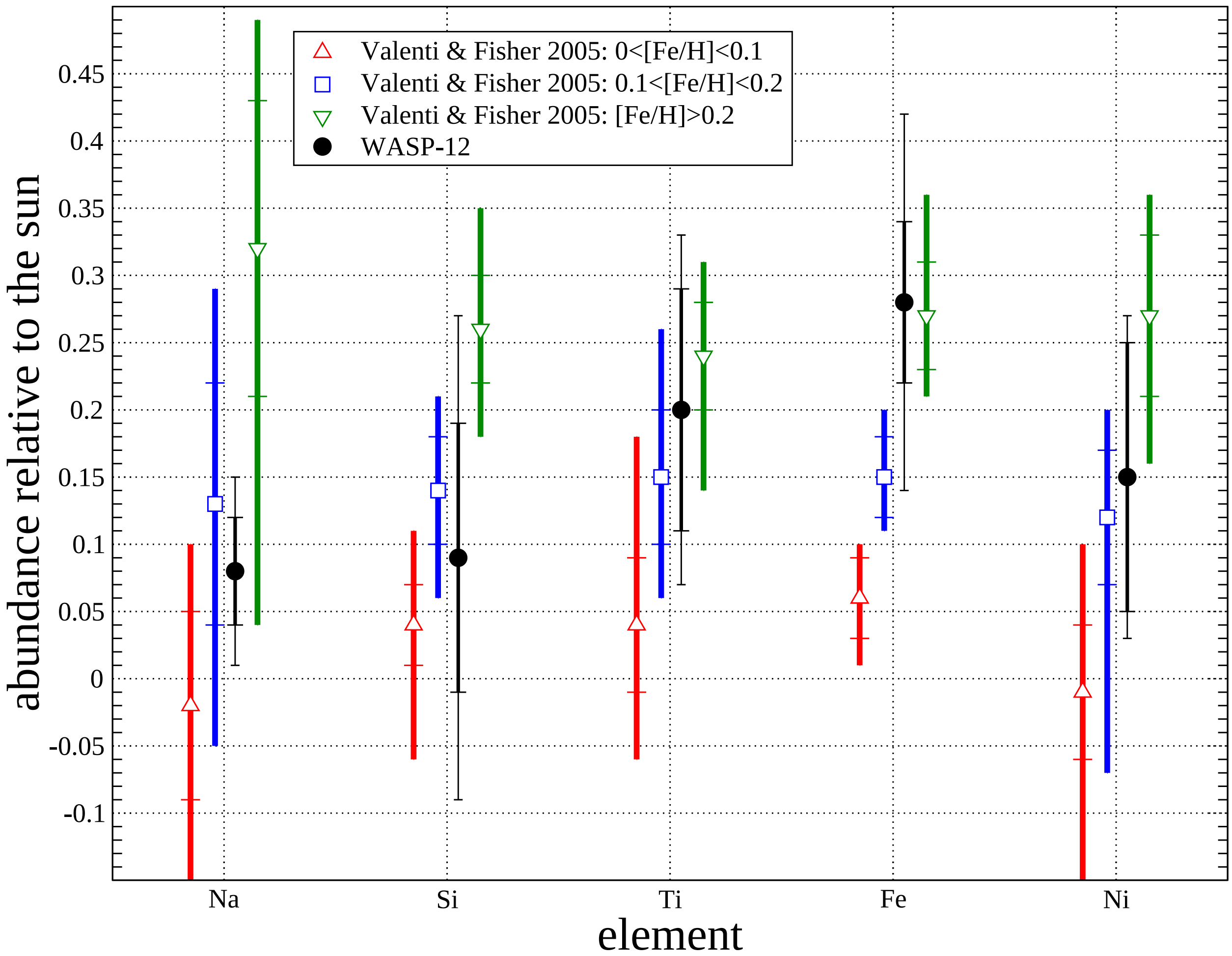

Fig. 10.— Comparison between the mean abundance, relative to the sun, of WASP-12 (full circles) and of the selected sample of stars from Valenti & Fisher (2005), that was subdivided according to the iron abundance: 0.0<[Fe/H]≤0.1 dex (open upside triangles), 0.1<[Fe/H]≤0.2 dex (open squares), and [Fe/H]>0.2 dex (open downside triangles). The shaded areas show the abundance range, while the error bars of the comparison sample give the standard deviation from the mean abundance. The uncertainties on the abundances of WASP-12 are as in Fig. 4.

abundance does not allow any firm conclusion. In summary the abundances of Ti and Fe follow the pattern of the high-metallicity stars, while Na, Si, and Ni seem to follow more the abundance pattern of the set of comparison stars with [Fe/H] between 0.1 and 0.2 dex.

The information gathered from this comparison lead to the conclusion that there is the possibility that the WASP-12 abundances of Na, Si, and Ni do not really match the abundance pattern that the WASP-12 iron abundance would suggest. But it has to be taken into account that the comparison is not free from systematic differences in the fundamental parameters and abundance determinations, and in the set of adopted atomic line parameters.

For a further search of possible abundance peculiarities in the atmosphere of WASP-12 we decided to compare our results with those of several other authors (Takeda et al. 2002; Sadakane et al. 2002; Ecuvillon et al. 2004; Sozzetti et al. 2006; Gilli et al. 2006; Santos et al. 2006; Bond et al. 2008; Neves et al. 2009) have obtained in planet hosting and non-planet hosting stars. In this way we should also be able to partially remove possible systematic differences in case a peculiar pattern becomes evident in the comparisons with several different authors.

The WASP-12 abundances we derived for O, Ca, Sc, Mn, Zn, Y, Zr, Nd, and Eu match very well the ones previously obtained by other authors in planet hosting and non-planet hosting stars, while abundances of Al, V, and Cu appear to be clearly below the values previously obtained by more than 0.2 dex. For the other compared elements (C, N, Na, Mg, Si, S, Ti, Cr, Co, and Ni) we obtained just a satisfactory agreement, since we register a tendency of the WASP-12 abundances of these elements to lay always in the lower margin of the comparison samples, in particular when the abundances are put in relation to the iron abundance. This result follows what previously obtained, strengthening the possibility of an increased Fe abundance in comparison to the one of some other elements.

In addition we compared our Si, Ti, and Ni WASP-12 abundances with the ones obtained by Robinson et al. (2006) in a set of planet hosting and non-planet hosting stars. We obtained a good agreement for Ti, but both Si and Ni appear to be depleted in WASP-12, compared to the abundances obtained by Robinson et al. (2006) in a set of planet hosting stars, therefore we cannot confirm their conclusion of a systematic enrichment of Si and Ni in planet hosting compared to non-planet hosting stars.

6.4. Spectral energy distribution: searching for a circumstellar disk

The circumstellar disk, predicted by Li et al. (2010) and tentatively observed by Fossati et al. (2010), could be detectable in the infrared. For this reason we decided to compare the calibrated Near-UV COS fluxes of WASP-12 and the available photometry (Johnson and 2MASS photometry) with synthetic fluxes obtained with LLmodels adopting the fundamental parameters and the abundances derived from the ESPaDOnS data, looking for an infrared excess in the 2MASS photometry. For this comparison, shown in Fig. 11, we took into account a reddening E(B-V)=0.126 mag (Amôres & Lépine 2005), that was calculated assuming the stellar distance obtained in Sect. 6.2.

Figure 11 shows a very good agreement between the model fluxes and the observations, demonstrating also the quality of both the adopted fundamental parameters and interstellar reddening.

Figure 11 does not show any clear infrared excess in the 2MASS photometry that could be interpreted as: (*i*) there is no interstellar disk around the star or (*ii*) the interstellar disk is not visible because either the emission is not strong enough or the emission peaks at much longer wavelengths. Li et al. (2010) suggested that the disk emission should peak at $\sim 2.3\,\mu$m, inside the wavelength range covered by the *K* band 2MASS photometry. Therefore, to look for an interstellar disk around WASP-12 it would be necessary to observe the system with a very high precision (Li et al. 2010) and at longer wavelengths, both accessible with the Herschel satellite

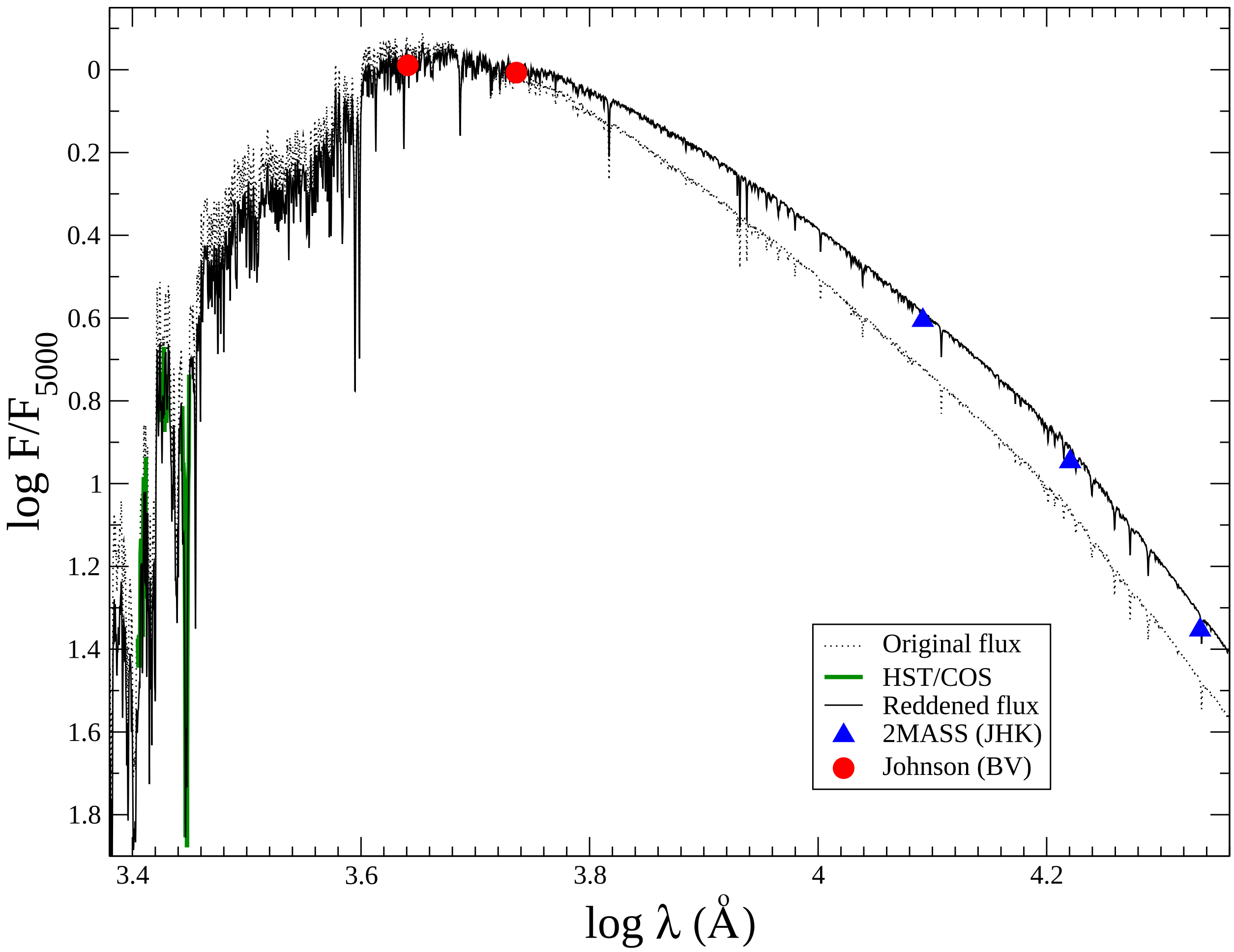

Fig. 11.— Comparison between LLmodels theoretical fluxes calculated with the fundamental parameters and abundances derived for WASP-12, taking into account a reddening of E(B-V)=0.126 mag (full line) and without taking into account reddening (dashed line), with COS calibrated fluxes (thick gray line), Johnson *BV* photometry (full points) and 2MASS photometry (full triangles). The error bars on the photometry have the same size of the symbols. The model fluxes and the COS spectra were convolved to have approximately a spectral resolution of 800, for display reasons.

(Pilbratt 2010).

7. Conclusions

On January 3rd and 5th 2010 we observed the planet hosting star WASP-12 with the ESPaDOnS spectropolarimeter with the aim of looking for a global magnetic field, derive the stellar parameters and perform a precise abundance analysis.

The WASP-12 fundamental parameters and iron abundance we obtained are in agreement with what previously published by Hebb et al. (2009): $T_{\rm eff}$=6250±100 K, $\log g$=4.2±0.2, $\upsilon_{\rm mic}$=1.2±0.3 km s^{-1}, and [Fe/H]=0.32±0.12 dex. $\upsilon \sin i$ is less than 4.6±0.5 km s^{-1}, while $\upsilon_{\rm macro}$ lays within the range 4.75–7.0±0.6 km s^{-1}. Dedicated observations to measure the amplitude of the RM effect are necessary to derive the real stellar $\upsilon \sin i$. The resultant metallicity of WASP-12 is Z=0.021±0.002 dex. A detailed analysis of the HR diagram, with the use of isochrones and evolutionary tracks allowed to derive more accurate ranges for the stellar age, mass and distance: the age of WASP-12 is between 1.0 Gyr Hebb et al. (2009) and 2.65 Gyr, the mass is between 1.23 and 1.49 $M/M_{\odot}$ (the last value comes from Hebb et al. 2009), and the distance to WASP-12 is between 295 and 465 pc. Our measurement of the Li abundance allowed us just to conclude that WASP-12 is older than 500 Myr.

We performed a magnetic field search adopting the LSD technique revealing that the star does not show any magnetic field signature in Stokes V. A detailed analysis of the possible star-planet magnetic interaction would require a time-dependent analysis of particular spectral lines, such as the Ca H & K lines (Shkolnik et al. 2003, 2005, 2008) and the Mg II UV resonance lines, but it has to be taken into account that WASP-12 shows a remarkably low stellar activity (Knutson et al. 2010), that will be analysed in detail in a forthcoming paper.

Given recent theoretical predictions (Li et al. 2010) and discoveries (Fossati et al. 2010), the WASP-12 system seems to be an ideal target to detect the presence of atmospheric pollution, due to the material lost by the planet. Therefore we looked for hints of pollution by looking for a correlation between the atmospheric element abundances and the condensation temperature, and by comparing the WASP-12 abundance pattern with the one of other planet hosting and non-planet hosting stars, previously published by several other authors. Our analysis revealed just the presence of hints of atmospheric pollution, although only a differential analysis would allow to obtain firm evidences. One must also take into account the fact that it is not clear whether WASP-12 would show the same kind of atmospheric pollution shown by the sun (Meléndez et al. 2009): the material coming from WASP-12 b and falling onto the star is in a gas/plasma state and only a detailed modeling of the temperature and density structure of the accretion disk would show whether the material is condensing in dust grains. If dust grains are forming it is likely that a differential analysis would reveal the kind of pollution signatures obtained for the sun, otherwise all the material lost by the planet would fall onto the star, making then the pollution signature dependent to the unknown hydrogen content of the planet.

With the use of the available HST calibrated spectra and of visible and infrared photometry, we looked for the presence of a circumstellar disk around WASP-12, but without success. Probably high precision far infrared measurements, such as those possible with the Hershel satellite, may reveal the presence of a circumstellar disk.

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