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Chemical composition of stars with brown dwarfs: exploring the transition from giant planets to brown dwarfs

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Abstract. The metal-rich nature of stars with giant planets is well known but low-mass planets do not require metal-rich enviroments to form, although at relatively low metallicities tend to form as companions of chemically alpha-enhanced stars. With the aim of studying the weak boundary that separates giant planets and brown dwarfs (BDs) and their formation mechanism, we have analyzed the CORALIE spectra of a sample of stars with already detected BD companions both by radial velocity and astrometry. Using standard tools we derived chemical abundances of these stars and compare them with those of stars hosting giant and small planets. We find that stars with BDs seem to have metallicities and chemical abundances in between those of giant planets and those of low-mass planets. Finally, the abundances of alpha-elements as a function of the minimum mass of the most-massive sub-stellar companion, from low-mass super-Earth like planets to massive BDs, display a maximum in abundance at a companion mass of $m_c \sin i \sim 1.2 - 1.6$ Jupiter masses. These results may suggest that the mechanism responsible for the formation of giant planets may be different to that of high-mass BD companions.

Key words. Stars: abundances – Stars: brown dwarfs – planets and satellites: formation – Stars: planetary systems – Stars: atmospheres

1. Introduction

Brown dwarf are substellar objects which do have enough mass to burn deuterium in their cores but not for hydrogen fusion (e.g. Burrows et al. 1997), with masses in the range 13 – 80 $M_{\rm Jup}$, i.e. in between the heaviest giant planets and the lightest stars. BDs were predicted by Kumar (1962) and Hayashi & Nakano

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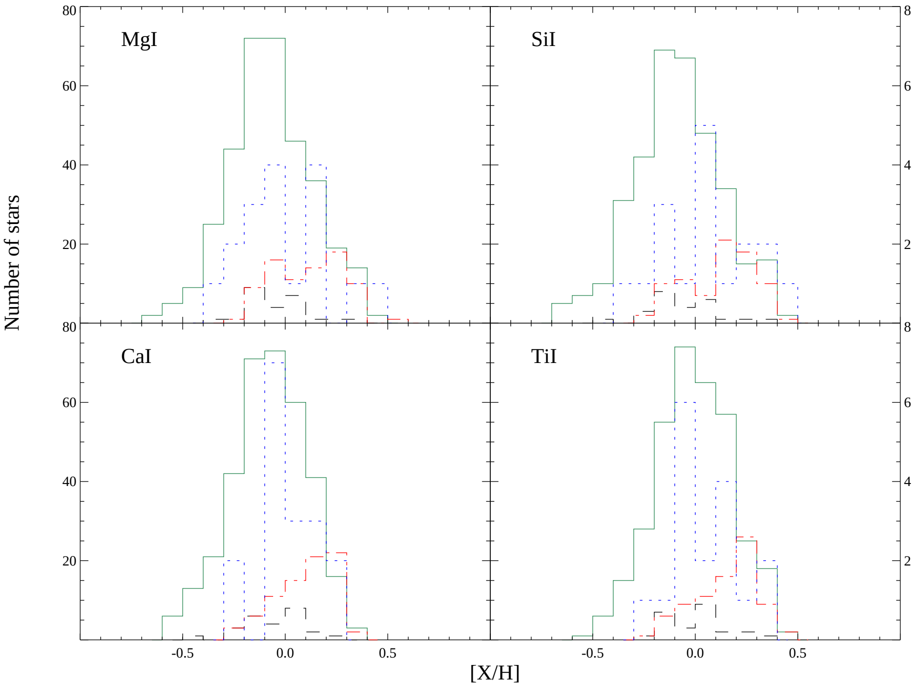

Fig. 1. Histograms of the α-element abundances, [X/H], for our samples of stars without planets ([green] solid line), stars with small planets ([black] solid line), stars with giant planets ([red] dashed line) and stars with BD companions ([blue] dashed line). The labels of left y-axis indicate the number of stars with and without planets whereas the right y-axis show the numbers of stars with BD companions.

(1963), but they were not empirically confirmed until 1995, when the first brown dwarf was detected (Teide 1; Rebolo et al. 1995). This happened the same year as the discovery of the first extra-solar planet (Mayor & Queloz 1995). The first BD companion to an M-dwarf star was also discovered that year (GJ 229B; Nakajima et al. 1995). During the following two decades high-precision radial velocity surveys have shown that close BDs around solar-type stars are scarcer than stars with planetary or stellar companions (e.g. Marcy & Butler 2000; Grether & Lineweaver 2006). This is the so-called "Brown dwarf desert".

2. Observations, sample and stellar parameters

Our sample has been extracted from F-, G- and K-type main-sequence stars of the CORALIE ($R \sim 50,000$) radial velocity (RV) survey (Udry et al. 2000). This sample consists of 15 stars with BD-companion candidates from Sahlmann et al. (2011), for which the minimum mass, $m_{\rm c} \sin i$, of most massive companion is in the brown-dwarf mass range ($13 - 80\,M_{\rm Jup}$). Sahlmann et al. (2011) were also able to derive the orbital inclination, i, by using astrometric measurements from Hipparcos (van Leeuwen 2007). This allowed them to confidently exclude as BD candidates six stars from the initial sample of 15 stars because the current mass determinations, $m_{\rm c}$, place them in the M-dwarf stellar regime. Stellar parameters of our sample were collected from Sahlmann et al. (2011) and Santos et al. (2005).

We have also made use of a HARPS subsample of 451 stars (Adibekyan et al. 2012), both with and without planetary companions. We collect the minimum mass of the most-

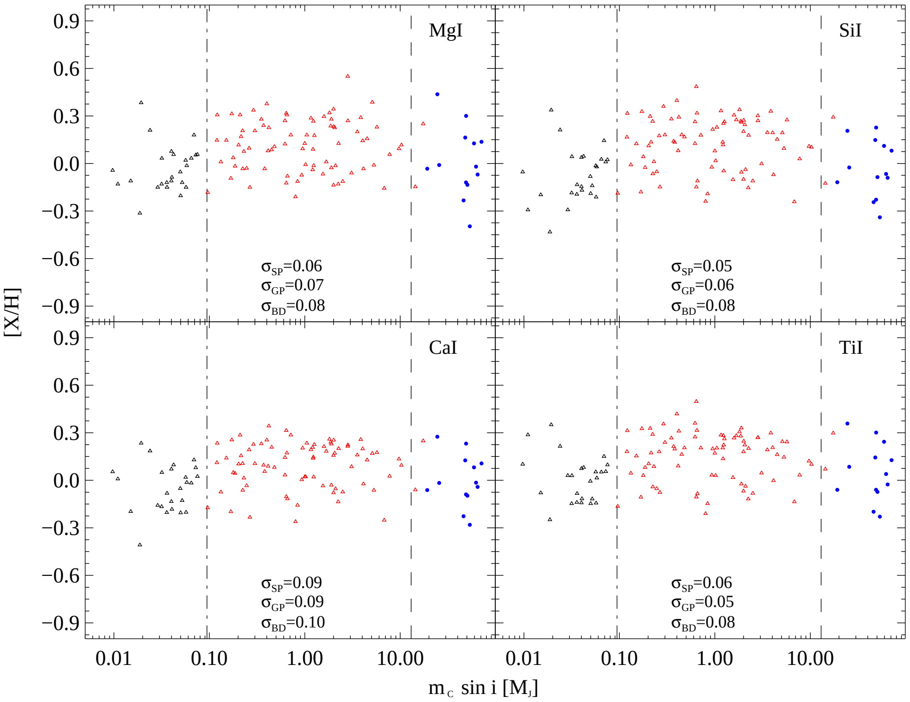

Fig. 2. α-element abundances [X/H] against minimum mass of the most-massive sub-stellar companion, $m_c \sin i$. Vertical dashed lines separates low-mass planets, high-mass planets and BDs.

massive planet in each planetary system from the encyclopaedia of extra-solar planets[1].

3. Chemical abundances

Chemical abundances were derived using standard tools. We compute EWs using the automatic code ARES (Sousa et al. 2007) and derive the chemical abundances as in Adibekyan et al. (2012). We use code MOOG[2] (Sneden 1973) in its version of 2010 with Kurucz ATLAS9 stellar model atmospheres (Kurucz 1993) for abundance determination.

We derive chemical abundances of the α-elements Mg, Si, Ca and Ti of the 15 stars in the BD-companion stellar sample. In Fig. 1 we display the histograms of chemical abundances of stars with and without planetary-mass companions from Adibekyan et al. (2012) together with those of stars with BD companions. The planetary-mass sample is separated in two groups: (i) small planets (super-Earth like and Neptune like planets) with masses of $m_c \sin i \lesssim 0.094\, M_{\rm Jup}$ ($\sim 30 M_\oplus$), and (ii) jovian planets with masses in the range $0.094 < m_c \sin i / M_{\rm Jup} < 13$. The stars with BD companions are also depicted for comparison. One can easily see that the sample of stars with giant planets appears to be more metal-rich than stars without planets (Santos et al. 2001). However, the α-element abundance distribution of stars with small planets resembles that of stars without planets (Neves et al. 2009; Adibekyan et al. 2012). Stars with BD companions instead seem to be slightly shifted to-

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[1] `http://exoplanet.eu`

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

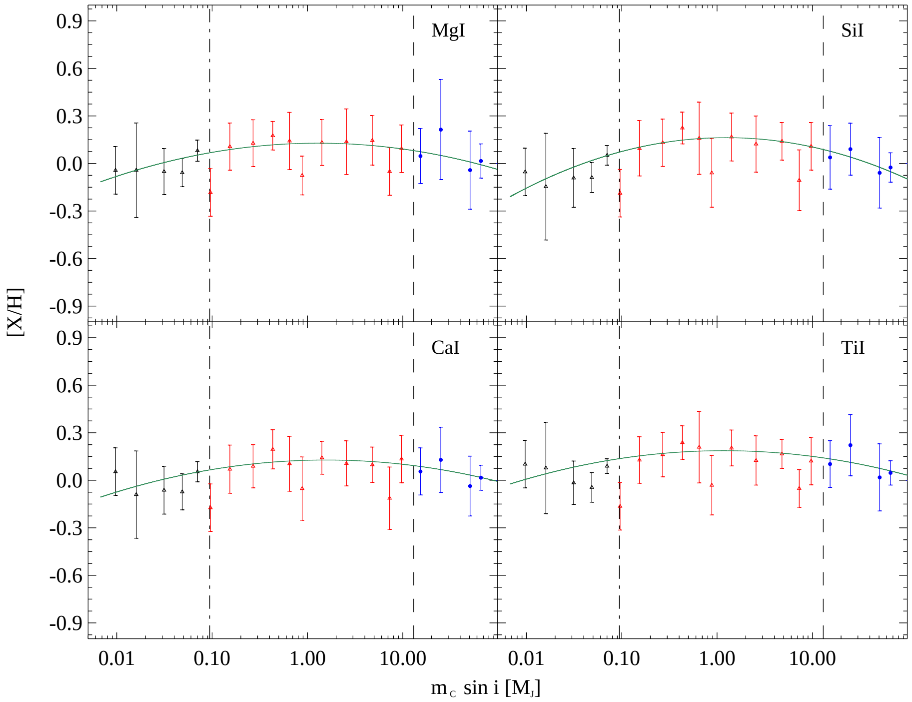

Fig. 3. Same as Fig. 2 but for the mean values in bins of $m_c \sin i$ which are roughly equidistant in logaritmic scale.

wards higher metallicites although not as much as stars with giant planets. Nevertheless, the sample of stars with BD companions is still very small to firmly confirm this statement.

4. Discussion and conclusions

The α-element abundances of stars with BD companions follow the Galactic thin-disk trend and exhibit roughly the same behaviour as those of stars with and without planets analyzed in previous works (Neves et al. 2009; Adibekyan et al. 2012).

The metal-content of stars at birth surely affects the formation of the planetary-mass companions, but is this also true for stars with BD companions? To answer this question we depicted in Fig. 2 the chemical abundances, [X/H], of α-elements as a function of the minimum mass of the most-massive substellar companion, that could be a small planet, a giant planet or a brown dwarf. The α-element abundances seem to progressively increase with the companion mass from small planets until reaching a maximum at about 1 $M_{\rm Jup}$ and then slightly decrease when entering in the BD regime. The scatter in [X/H] may be due to the different intrinsic metallicities of the stars at every bin in $m_c \sin i$.

In Fig. 3 we display the mean values of the α-element abundances [X/H] in bins of $m_c \sin i$. The mean values show an increasing trend from low-mass up to Jupiter-mass planets and then decreasing trend towards high-mass BD companions. We fit a parabolic function to the mean values of the abundances of each α-element. The peaks of all these trends have a maximum at about 1.2–1.6 $M_{\rm Jup}$. This behaviour still holds if we remove the six stars which may be discarded as BDs (Sahlmann et al. 2011).

Sahlmann et al. (2011) noticed that there is a lack of BD companions with masses in the range $m_\mathrm{c}\sin i \sim 35$–$55\,M_\mathrm{Jup}$. More recently, Ma & Ge (2013) have collected the known BD companions from different studies and confirm this gap for stars with for periods shorter than 100 days. Although the statistics may be still poor these authors suggest that BD companions below this gap, i.e. with $m_\mathrm{c}\sin i < 42\,M_\mathrm{Jup}$, may have form in protoplanetary disks as giant planets, probably through the disk instability-fragmentation mechanism (Boss 1997; Stamatellos & Whitworth 2009), whereas BD companions with $m_\mathrm{c}\sin i > 42\,M_\mathrm{Jup}$ may have form by molecular cloud fragmentation as stars (Padoan & Nordlund 2004; Hennebelle & Chabrier 2008).

Our results, although probably not statistically significant due to the very few stars with confirmed BD companions, tentatively suggest that stars with BD companions at masses $m_\mathrm{c}\sin i$ below $42\,M_\mathrm{Jup}$ may have similar α-element abundances to those of giant-planet hosts. On the other hand, stars with massive BDs may have an abundance pattern that resembles that of stars without planets. This may support the above statement with the low-mass BD companions being formed in protoplanetary disks as giant planets, and the high-mass BDs being formed by cloud fragmentation as star.

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