Four new planets around giant stars and the mass-metallicity correlation of planet-hosting stars. *

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ABSTRACT

Context. Exoplanet searches have revealed interesting correlations between the stellar properties and the occurrence rate of planets. In particular, different independent surveys have demonstrated that giant planets are preferentially found around metal-rich stars and that their fraction increases with the stellar mass.

Aims. During the past six years, we have conducted a radial velocity follow-up program of 166 giant stars, to detect substellar companions, and characterize their orbital properties. Using this information, we aim to study the role of the stellar evolution in the orbital parameters of the companions, and to unveil possible correlations between the stellar properties and the occurrence rate of giant planets.

Methods. We have taken multi-epoch spectra using FEROS and CHIRON for all of our targets, from which we have computed precision radial velocities and we have derived atmospheric and physical parameters. Additionally, velocities computed from UCLES spectra are presented here. By studying the periodic radial velocity signals, we have detected the presence of several substellar companions.

Results. We present four new planetary systems around the giant stars HIP8541, HIP74890, HIP84056 and HIP95124. Additionally, we study the correlation between the occurrence rate of giant planets with the stellar mass and metallicity of our targets. We find that giant planets are more frequent around metal-rich stars, reaching a peak in the occurrence of giant planets with Fe/H ~ 0.35 dex. Similarly, we observe a positive correlation of the planet occurrence rate with the stellar mass, between M* = 1.0 - 2.1 M⊙, with a maximum of f = 13.0 ± 1.1 %, at M* = 2.1 M⊙. Our conclusion is that giant planets are preferentially found around metal-rich stars. We conclude that they are more efficiently formed around more massive stars, in the stellar mass range of ~ 1.0 - 2.1 M⊙. These observational results confirm previous findings for solar-type and post-MS hosting stars, and provide further support to the core-accretion formation model.

Key words. techniques: radial velocities - Planet-star interactions - (stars:) brown dwarfs

1. Introduction

Twenty years after the discovery of 51 Peg b (Mayor & Queloz 1995), we count more than 1600 confirmed extrasolar planets. In addition, there is a long list of unconfirmed systems from the Kepler mission (Borucki et al. 2010), adding up more than 5000 candidate exoplanets that await confirmation. These planets have made great acceptance in the exoplanet field, since the metallicity and the occurrence rate of giant planets (the so-called ‘planet-metallicity’ correlation; PMC hereafter). The PMC has gained much interest in the exoplanet field, since the metallicity and the occurrence rate of giant planets (the so-called ‘planet-metallicity’ correlation; PMC hereafter). This relationship was initially proposed by Gonzalez et al. (1997), and has been confirmed by subsequent studies (Santos et al. 2001, Fischer & Valenti 2005, hereafter).
FIS05). Moreover, by comparing the host-star metallicity of 20 sub-stellar companions from the literature with the metallicity distribution of the Lick sample, Hekker et al. (2007) showed that planet-hosting stars are on average more metal rich by 0.13 ± 0.03 dex, suggesting that the PMC might also be valid for giant stars. However, recent works have obtained conflicting results, particularly from planet search programs focusing on post-main-sequence (MS) stars. For instance, Pasquini et al. (2007), based on a sample of 10 planet-hosting giant stars, showed that exoplanets around evolved stars are not found preferentially in metal-rich systems, arguing that the planet-metallicity correlation might be explained by an atmospheric pollution effect, due to the ingestion of iron-rich material or metal-rich giant planets (Murray & Chaboyer 2002). Similarly, Hekker et al. (2008) showed a lack of correlation between the planet occurrence rate and the stellar metallicity, although they included in the analysis all of the giant stars with observable periodic radial velocity (RV) variations, instead of only including those stars with secure planets. Thus, it might be expected that the Hekker et al. sample is contaminated with non-planet-hosting variable stars. Döllinger et al. (2009) showed that planet-hosting giant stars from the Tautenburg survey tend to be metal-poor. In contrast, based on a small sample of subgiant stars with $M > 1.4 M_\odot$, Johnson et al. (2010; hereafter JOHN10) found that their data are consistent with the planet-metallicity correlation observed among dwarf stars. Also, Maldonado et al. (2013) showed that the planet-metallicity correlation is observed in evolved stars with $M > 1.5 M_\odot$, while for the lower mass stars this trend is absent. Finally, based on a much larger sample analyzed in a homogeneous way, Reffert et al. (2015; hereafter REF15) showed that giant planets around giant stars are preferentially formed around metal-rich stars.

On the other hand, different RV surveys have also shown a direct correlation between the occurrence rate of giant planets and the stellar mass. Johnson et al. (2007), claimed that there is a positive correlation between the fraction of planets and stellar mass. They showed that the fraction increases from $f = 1.8 \pm 1.0 \%$, for stars with $M_* < 0.4 M_\odot$ to a significantly higher value of $f = 8.9 \pm 2.9 \%$, for stars with $M_* > 1.6 M_\odot$. These results were confirmed by JOHN10, who showed that there is a linear increase in the fraction of giant planets with the stellar mass, characterized by $f = 2.5 \pm 0.9 \%$, for $M_* < 0.4 M_\odot$ and $f = 11.0 \pm 2.0 \%$, for $M_* > 1.6 M_\odot$. In a similar study, Bowler et al. (2014) showed that the fraction of giant planets hosted by stars with mass between 1.5 - 1.9 $M_\odot$ is $f = 26\%$, significantly higher than the value obtained by JOHN10.

In this paper we present the discovery of four giant planets around giant stars that are part of the EXPRESS (EXoPlanets around Evolved StarS) radial velocity program (Jones et al. 2011; hereafter JON11). The minimum masses of the substellar companions range between 2.4 and 5.5 $M_\oplus$, and have orbital periods in the range 562-1560 days. All of them have low eccentricity values $e < 0.16$. In addition to these planet discoveries, we present a detailed analysis of the mass-metallicity correlations of the planet-hosting and non-planet-hosting stars in our sample, along with studying the fraction of multiple-planet systems observed in giant stars.

This paper is organized as follows. Section 2 briefly describes the observations and radial velocity computation techniques. In Section 3 we summarize the main properties of the host stars. In Section 4, we present a detailed analysis of the orbital fits and stellar activity analysis. In Section 5 we present a statistical analysis of the mass-metallicity correlation of our host stars. Also, we discuss about the occurrence rate of multiple-planet systems. The summary and discussion are presented in Section 6.

2. Observations and RV calculation

Since 2009 we have been monitoring a sample of 166 bright giant stars that are observable from the southern hemisphere. The selection criteria of the sample are presented in JON11. We have been using two telescopes located in the Atacama desert in Chile, namely the 1.5 m telescope at the Cerro Tololo Inter-American Observatory and the 2.2 m telescope at La Silla observatory. The former was initially equipped with the fiber-fed echelle spectrograph (FEROS), which was replaced in 2011 by CHIRON (Tokovinin et al. 2013), a much higher resolution and more stable spectrograph. These two spectrographs are equipped with an I$_2$ cell, which is used as a precision wavelength reference.

The 2.2 m telescope is connected to the Fiber-fed Extended Range Optical Spectrograph (FEROS; Kaufer et al. 1999) via optical fibres to stabilise the pupil entering the spectrograph. FEROS offers a unique observing mode, delivering a spectral resolution of ~48,000, and does not require the beam be passed through an I$_2$ cell for precise wavelength calibration, using a Thorium-Argon gas lamp instead.

We have taken several spectra for each of the stars in our sample using these instruments. In the case of FERCH and CHIRON, we have computed precision radial velocities using the iodine cell method (Butler et al. 1996). We achieve typically a precision of ~10-15 m s$^{-1}$ from FERCH data, and ~5 m s$^{-1}$ for CHIRON. On the other hand, for FEROS spectra, we used the simultaneous calibration method (Baranne et al. 1996) to extract the stellar radial velocities, reaching a typical precision of ~5 m s$^{-1}$. Details on the data reduction and RV calculations have been given in several papers (e.g. Jones et al. 2013; 2014; 2015a, 2015b). In addition, we present complementary observations from the Pan-Pacific Planet Search (PPPS; Wittenmyer et al. 2011). These spectroscopic data have been taken with the UCLES spectrograph (Diego et al. 1999), which delivers a resolution of R ~ 45,000, using a 1 arcsec slit. The instrument is mounted on the 3.9 m Anglo-Australian telescope and is also equipped with an I$_2$ cell for wavelength calibration. Details on the reduction procedure and RV calculations can be found in Tinney et al. (2001) and Wittenmyer et al. (2012).

3. Host stars properties

Table I lists the stellar properties of HIP 8541 (= HD 113431), HIP 74890 (= HD 135760), HIP 84056 (= HD 155233) and HIP 95124 (= HD 181342). The spectral type, B - V color, visual magnitude, and parallax of these stars were taken from the Hipparcos catalog (van Leeuwen 2007). The atmospheric parameters ($T_{\text{eff}}$, logg, [Fe/H], vsini) were computed using the MOOG code (Sneden 1973), following the methodology described in JON11. The stellar mass and radius were derived by comparing the position of the star in the HR diagram with the evolutionary tracks from Salasnich et al. (2000). A detailed description of the method is presented in Jones et al. (2011; 2015b).

3 CHIRON delivers a maximum resolution of ~130,000 using the narrow slit mode.

4 http://www.as.utexas.edu/~chris/moog.html
4. Orbital parameters and activity analysis

4.1. HIP8541 b

We have computed a total of 36 precision RVs of HIP8541, from FEROS, CHIRON, and UCLES spectra taken between 2009 and 2015. These velocities are listed in Table A.1 and are shown in Figure 1. As can be seen, there is a large RV signal with an amplitude that exceeds the instrumental uncertainties, and the RV jitter expected for the spectral type of this star (e.g. Sato et al. 2005), by an order of magnitude. A Lomb-Scargle periodogram (Scargle 1982) revealed a strong peak around \( \sim 1600 \) days. Starting from this orbital period, we computed the Keplerian solution using the Systemic Console version 2.17 (Meschiari et al. 2009). To do this, we added a 5 m s\(^{-1}\) rejection method to remove outliers, which are typically due to CCD saturation. The photometric stability of the HIP 74890 radial velocities. Finally, we computed the S-index variations from the reversal core emission of the Ca\( ii \) H and K lines, according to the method presented in Jenkins et al. (2008, 2011), revealing no significant correlation with the measured velocities.

4.2. HIP74890 b

The velocity variations of HIP 74890 are listed in Table A.2. The RVs were computed from FEROS and UCLES spectra, taken between the beginning of 2009 and mid 2015. A detailed analysis of the RV data revealed a periodic signal, which is superimposed onto a linear trend. The best Keplerian fit is best explained by a giant planet with a projected mass of 2.4 M\(_J\) and an orbital distance of 5.7 AU, respectively. Figure 2 shows the HIP 74890 radial velocities.

The Hipparcos and ASAS photometric datasets of this stars present a stability of 0.008 mag and 0.013 mag, respectively. No
significant peak is observed in the LS periodogram of these two datasets. Similarly, the BVS analysis, CCF variations, and chromospheric activity analysis show neither an indication of periodic variability, nor any correlation with the radial velocities.

4.3. HIP84056 b

The velocity variations of HIP 84056 are listed in Table A.3 and Figure 3 shows its RV curve. The best orbital solution leads to: $P = 818.8 \pm 12.1$ days, $m_\mathrm{p} \sin i = 2.6 \pm 0.3$ and $e = 0.04 \pm 0.04$. The full orbital elements solution are listed in Table 2. This planet was independently detected by the PPPS (Wittenmyer et al. 2016). Based on 21 RV epochs, they obtained an orbital period of $885 \pm 63$ days, minimum mass of $2.0 \pm 0.5M_\odot$, and eccentricity of $0.03 \pm 0.02$, in good agreement with our results.

To determine the nature of the periodic RV signal observed in HIP84056, we performed an activity analysis, as described in section 4.1. We found no significant periodicity or variability of the activity indicators with the observed RVs. Moreover, the photometric analysis of the Hipparcos data reveals a stability of 0.009 mag. Similarly, the RMS of the ASAS data is 0.012 mag. These results support the planet hypothesis of the periodic signal detected in the RVs.

4.4. HIP95124 b

Figure 4 shows the RV variations of HIP95124. The orbital parameters are listed in Table 2. The RV variations of HIP 8541 are best explained by the presence of a $2.9 \pm 0.2 M_\odot$ planet, with orbital period of $P = 562.1 \pm 6.0$ days and eccentricity $e = 0.1 \pm 0.07$. The radial velocities are also listed in Table A.3. As for the other stars described here, we scrutinized the Hipparcos and ASAS photometry to search for any signal with a period similar to that observed in the RV timeseries, finding a null result. Moreover, the Hipparcos and ASAS RMS is 0.007 mag and 0.013 mag. According to Hatzes (2002), this photometric variability is well below the level to mimic the RV amplitude observed in this star. Additionally, the BVS, CCF variations, and S-index variations show no significant correlation with the observed radial velocities.

5. Preliminary statistical results of the EXPRESS project

After 6 years of continuous monitoring of a sample comprised by 166 giant stars, we have published a total of 11 substellar companions (including this work), orbiting 10 different stars. In addition to this, using combined data of the EXPRESS and PPPS surveys, we have detected a two-planet system in a 3:5 mean-motion resonance (Wittenmyer et al. 2015) around the giant star HIP 24275. Moreover, Trifonov et al. (2014), recently an-
Table 2. Orbital parameters

|                | HIP8541b | HIP74890b | HIP84056b | HIP95124b |
|----------------|----------|-----------|-----------|-----------|
| P (days)       | 1560.2 ± 53.9 | 822.3 ± 16.8 | 818.8 ± 12.1 | 562.1 ± 6.0 |
| K (m s⁻¹)      | 87.4 ± 6.4   | 36.5 ± 2.7  | 40.5 ± 3.1  | 46.5 ± 1.8 |
| a (AU)         | 2.8 ± 0.25   | 2.1 ± 0.09  | 2.0 ± 0.06  | 1.65 ± 0.04 |
| e              | 0.16 ± 0.06  | 0.07 ± 0.07  | 0.04 ± 0.04  | 0.10 ± 0.07 |
| Mₚsin²(Mₚ)     | 5.5 ± 1.0    | 2.4 ± 0.3   | 2.6 ± 0.3   | 2.9 ± 0.2   |
| ω (deg)        | 293.9 ± 15.2 | 181.9 ± 93.9 | 120.0 ± 71.9 | 311.8 ± 35.8 |
| T_p-24550000   | 4346.9 ± 93.4 | 4820.4 ± 379.8 | 5282.0 ± 192.1 | 4915.5 ± 54.3 |
| γ (m s⁻¹ yr⁻¹) | ---        | -33.23 ± 1.46 | ---         | ---         |
| γ₁ (m s⁻¹)     | 58.8 ± 4.1   | ---        | 6.7 ± 2.3   | 24.6 ± 3.0  |
| γ₂ (m s⁻¹)     | -56.7 ± 5.6  | 78.1 ± 3.6  | 3.6 ± 2.7   | -1.4 ± 2.6  |
| γ₃ (m s⁻¹)     | -14.3 ± 5.0  | 80.3 ± 4.3  | ---        | 4.8 ± 5.0   |
| RMS (m s⁻¹)    | 9.1         | 6.5        | 9.9        | 7.2        |
| χ²_red         | 2.4         | 1.5        | 2.7        | 1.7        |

nounced the discovery of a two-planet systems around HIP 5364, as part of the Lick Survey (Frink et al. 2002). Since this star is part of our RV program, we have also taken several FECH and CHIRON spectra. The resulting velocities will be presented in a forthcoming paper (Jones et al., in preparation).

In summary, a total of 15 substellar companions to 12 different stars in our sample have been confirmed, plus a number of candidate systems that are currently being followed-up (Jones et al. in preparation). These objects have projected masses in the range 1.4 - 20.0 M☉, and orbital periods between 89 d (0.46 AU) and 2132 d (3.82 AU).

Figure 5 shows the orbital distance versus stellar mass for these 12 systems. The red and blue dashed lines represent radial velocity amplitudes of K = 30 m s⁻¹ (assuming circular orbits), which correspond to ~ 3-σ detection limits. It can be seen that we can detect planets with Mₚ > 3.0 M_J up to a ~ 3 AU (or Mₚ > 2.5 M_J at a ~ 2.5 AU) around stars with M_* < 2.5 M_☉. For more massive stars, we can only detect such planets but at closer orbital distance (a < 2.5 AU for M_* = 3.0 M_☉). We note that we have collected at least 15 RV epochs for each of our targets, with a typical timespan of ~2-3 years, which allow us to efficiently detect periodic RV signals with K ≥ 30 m s⁻¹ and e ≤ 0.6 via periodogram analysis and visual inspection. Moreover, we have obtained additional data for our targets showing RV variability ≥ 20 m s⁻¹, including those presenting linear trends. In fact, some of these linear trend systems are brown-dwarf candidates, with orbital periods exceeding the total observational timespan of our survey (P ≥ 2200 d; see Bluhm et al., submitted). We also note that in the case of HIP 67851 c (Jones et al. 2015b), we used ESO archive data to fully cover its orbital period (P = 2132 d; a = 3.82 AU).

5.1. Stellar mass and metallicity

Figure 6 shows a histogram of the planetary occurrence rate as a function of the stellar mass in our sample. The bin width is 0.4 M_☉ and the stellar masses range from 0.9 M_☉ to 3.5 M_☉. The uncertainties were computed according to Cameron (2011), and correspond to 68.3% equal-tailed confidence limits. As can be seen, there is an increase in the detection fraction with the stellar mass, between ~0.7 - 2.1 M_☉, reaching a peak in the occurrence rate of f = 13.0 ± 0.7%. For M_* = 2.1 M_☉, in addition, there is a sharp drop in the occurrence rate at stellar masses ≥ 2.5 M_☉. In fact, there are 17 stars in our survey in this mass regime, but none of them host a planet. We note that, although the observed lack of planets around these stars might be in part explained by the reduced RV sensitivity (see Figure 5), all of our targets more massive than 2.5 M_☉ present RV variability ≤ 15 m s⁻¹. This means that we can also discard the presence of planets with Mₚ ≥ 3.0 M_J interior to a ~ 3 AU, otherwise we would expect to observe doppler-induced variability at the ≥ 20 m s⁻¹ level. Following the REFL results, we fitted a Gaussian function to the data, of...
the form:

\[ f(M_\star) = C \exp \left( \frac{-(M_\star - \mu)^2}{2\sigma^2} \right), \]

To obtain the values of \( C, \mu \) and \( \sigma \), we generated 10000 synthetic datasets, computing the confidence limits for each realization following the Cameron (2011) prescription. After fitting \( C, \mu \) and \( \sigma \) for each synthetic dataset, we end-up with a probability density distribution for each of these three parameters. We note that we first computed \( C \) and then we fixed it to compute \( \mu \) and \( \sigma \), restricting these two parameters to: \( \mu \in [1.5,3.0] \) and \( \sigma \in [0.0,1.5] \). Figure 7 shows our results for the three parameters. The red lines correspond to the smoothed distributions. We obtained the following values: \( C = 0.14^{+0.08}_{-0.03} \), \( \mu = 2.29^{+0.44}_{-0.06} M_\odot \), and \( \sigma = 0.64^{+0.44}_{-0.04} M_\odot \). The parameters were derived from the maximum value and equal-tailed confidence limits of each smoothed distribution, respectively.

Despite the fact that we are dealing with low number statistics, particularly for the upper mass bin, these results are in excellent agreement with previous works. JOHN10, based on a sample of 1266 stars with \( M_\star \sim 0.5-2.0 M_\odot \), showed that the occurrence rate of planets increases linearly with the mass of the host star, reaching a fraction of \( \sim 14 \% \) at \( M_\star \sim 2.0 M_\odot \). Similarly, based on a sample of 373 giant stars with \( M_\star \sim 1.0-5.0 M_\odot \), REF15 showed that the detection fraction of giant planets present a Gaussian distribution, with a peak in the detection fraction of \( \sim 8 \% \) at \( M_\star \sim 1.9 M_\odot \). Additionally, they showed that the occurrence rate around stars more massive than \( \sim 2.7 M_\odot \) is consistent with zero, in good agreement with our findings, and also with theoretical predictions. For instance, based on a semi-analytic calculation of an evolving snow-line, Kennedy & Kenyon (2008) showed that the formation efficiency increases linearly from 0.4 to 3.0 \( M_\odot \). For stars more massive than 3.0 \( M_\odot \), the formation of gas giant planets in the inner region of the protoplanetary disk is strongly reduced. Because of the fast stellar evolution timescale for those massive stars, the snow line moves rapidly to 10-15 AU, preventing the formation of the giant planets in this region.

Figure 6 shows the planet occurrence rate as a function of the stellar metallicity. The symbols and lines are the same as in Figure 6. The width of the bins is 0.15 dex. It can be seen, that the occurrence rate increases with the stellar metallicity, with a peak of \( f = 16.7^{+5.5}_{-5.9} \% \) around stars with \( [\text{Fe/H}] = 0.35 \) dex. This trend seems to be real, despite a relatively high fraction observed in the bin centered at -0.25 dex, which might be explained by the low number statistics for that specific bin. Following the prescription of FIS05, we fitted the metallicity dependence of the occurrence fraction, with a function of the form:

\[ f([\text{Fe/H}]) = \alpha 10^{\beta [\text{Fe/H}]} \]
stars with detected planets \( (n_p) \), number of stars in the bin \( (n_s) \) and the fraction of stars with planets in each bin \( (f) \), are listed in columns 3-5. It can be seen that the highest fraction is obtained in the bin centered at \( 1.4 \, M_\odot \) and \( 0.12 \, \text{dex} \) \( (f = 9.4 \pm 3.5) \), which is slightly higher than the value of the bin with the same metallicity, but centered at \( 2.2 \, M_\odot \) \( (f = 9.1 \pm 0.8) \). Interestingly, REF15 found a similar trend, i.e., they also obtained the highest fraction in these two mass-metallicity bins, although they claim higher values for \( f \). Also, we analyzed the combined results of the two surveys. These are listed in columns 6-8 in Table 3. It can be seen that the overall trend is unaffected, but the uncertainties in the planet fraction are smaller.

Finally, to understand whether the combined results are affected by systematic differences in the stellar parameters derived independently by the two surveys, we compared the resulting metallicities of the Lick Survey (listed in REF15) with those derived using our method. We used a total of 16 stars, from which 12 of them are common targets. We measured a difference of \( \Delta(\text{Fe/H}) = 0.03 \, \text{dex} \pm 0.11 \, \text{dex} \), showing the good agreement between the two methods. Similarly, we compared the masses of the stars derived by the two surveys. We found that our stellar masses are on average larger by \( \Delta(M_\star) = 0.15 \pm 0.37 \, M_\odot \), which corresponds to a ratio of \( 1.07 \pm 0.18 \). For comparison, Niedzielski et al. (2016) also found that our stellar masses are overestimated with respect to their values by a factor \( 1.15 \pm 0.10 \).

We also note that the planet-hosting star HIP 5364 is a common target of the two surveys. They obtained \( T_{\text{eff}} = 4528 \pm 19 \, \text{K} \) and \( \text{[Fe/H]} = 0.07 \pm 0.1 \) dex. Using these values they derived a mass of \( 1.7 \pm 0.1 \, M_\odot \) for this star (Trifonov et al. 2014), significantly lower than our value of \( 2.4 \pm 0.3 \, M_\odot \). This shows that the combined results of the Lick and EXPRESS surveys should be taken with caution. Certainly, a more detailed comparison between the stellar parameters derived independently by the two surveys, as well as their completeness, will allow us to check the validity of these combined results.

5.2. Multiple-planet systems.

Out of the 12 planet-hosting stars in our sample, HIP 5364, HIP 24275 and HIP 67851 host planetary systems with at least two giant planets. This means that 25% of the parent stars, host a multiple system. Considering the full sample, it yields a \( \sim 2 \% \) fraction of multiple systems, comprised by two or more giant planets \( (M_p > 1.0 \, M_J) \). This number is a lower limit, since there are several other systems in our sample whose velocities are compatible with the presence of a distant giant planet, but still need confirmation (e.g. HIP 74890, presented in section 4.2).

If we consider all of the known planet-hosting giant stars (\( \log g \leq 3.6 \)), around 10% of them host a planetary system comprised by at least two giant planets. This fraction is significantly higher compared to solar-type stars. In fact, there are only 21 such systems among dwarf stars, despite the fact that most of them

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[7] Our typical dispersion (RMS) in the metallicity derived by each of the \( \sim 150 \, \text{Fe I} \) individual lines is \( \sim 0.1 \, \text{dex} \), corresponding to an internal error \( \leq 0.01 \, \text{dex} \).

[8] source: [http://exoplanets.org](http://exoplanets.org)
the RV surveys have targeted those type of stars. Moreover, planets are easier to be detected via precision RVs around solar-type stars, because they are on average less massive and have p-modes oscillations much weaker than giant stars (Kjeldsen & Bedding 1995), which translates into larger amplitudes with a lower level of RV noise. This observational result is a natural extension of the known mass distribution of single-planet systems orbiting evolved stars, which is characterized by an overabundance of super-Jupiter-like planets (e.g. Lovis & Mayor 2007; Döllinger et al. 2009; Jones et al. 2014). This result also reinforces the observed positive correlation between the stellar and planetary mass, in the sense that more massive stars not only tend to form more massive single planets, but also more massive multi-planet systems.

6. Summary and discussion

In this work we present precision radial velocities of four giant stars that have been targeted by the EXPRESS project, during the past six years. These velocities show periodic signals, with semi-amplitudes between ~ 50 - 100 m s⁻¹, which are likely caused by the doppler shift induced by orbiting companions. We performed standard tests (chromospheric emission, line bisector analysis and photometric variability) aimed at studying whether these RV signals have an intrinsic stellar origin. We found no correlation between the stellar intrinsic indicator with the observed velocities. Therefore, we conclude that the most probable explanation of the periodic RV signals observed in these stars is the presence of substellar companions. The best Keplerian fit to the RV data of the four stars leads to minimum masses between mₚ sin i = 2.4 - 5.5 M_J and orbital periods P = 562 - 1560 days. Interestingly, all of them have low eccentricities (e ≤ 0.16), confirming that most of the giant planets orbiting evolved stars present orbital eccentricities ≤ 0.2 (Schaufman & Winn 2013; Jones et al. 2014). The RVs of HIP 74890 also reveal the presence of a third object at large orbital separation (a > 6.5 AU). The RV trend induced by this object is most likely explained by a brown dwarf or a stellar companion.

We also present a statistical analysis of the mass-metallicity correlations of the planet-hosting stars in our sample. This sub-sample is comprised of 12 stars, drawn from a parent sample of 166 stars, which host a total of 15 giant planets. We show that the fraction of giant planets f, increases with the stellar mass in the range between ~ 1.0 - 2.1 M_☉, despite the fact that planets are more easily detected around less massive stars. For comparison, we obtained f = 2.6 ± 0.4% for M_☆ ~ 1.3 M_☉, and a peak of f = 13.0 ± 1.1% for stars with M_☆ ~ 2.1 M_☉. These results are in good agreement with previous works showing that the occurrence rate of giant planets exhibit a positive correlation with the stellar mass, up to M_☆ ~ 2.1 M_☉ (e.g. JOHN10; REF15). For stars more massive than ~ 2.5 M_☉, the fraction of planets is consistent with zero. We fitted the overall occurrence distribution with a Gaussian function (see Eq. 1), obtaining the following parameters: C = 0.14 ± 0.08, μ = 2.29 ± 0.44 M_☉, and σ = 0.64 ± 0.43 M_☉.

Similarly, we studied the occurrence rate of giant planets as a function of the stellar metallicity. We found an overabundance of planets around metal-rich stars, with a peak of f = 16.7 ± 13.5% for stars with [Fe/H] ~ 0.35 dex. We fitted the metallicity dependence of the occurrence rate with a function of the form f = α [Fe/H] β, obtaining the following parameter values: α = 0.061 ± 0.003, and β = 1.27 ± 0.82 dex⁻¹. Our power-law index β lies in between the values measured by JOHN10 (β = 1.2 ± 0.2) and FIS05 (β = 2.0). Thus, our results suggest that the planet-metallicity correlation observed in solar-type stars is also present in intermediate-mass (M_☆ ≥ 1.5 M_☉) evolved stars, in agreement with REF15 results.

Finally, we investigated the fraction of multiple planetary systems comprised by two or more giant planets. Out of the 12 systems presented above, three of them contain two giant planets, which is a significant fraction of the total number of these planetary systems. If we also consider multi-planet systems published by other RV surveys, we found that there is a significantly higher fraction of them around intermediate-mass evolved stars in comparison to solar-type stars. This result is not surprising, since different works have shown that giant planets are more frequent around intermediate-mass stars (Döllinger et al. 2009; Bowler et al. 2010). Thus, we conclude that the high fraction of multiple systems observed in giant stars is a

| [Fe/H] (dex) | M_☆ (M_☉) | n_p | n_s | f (%) | EXPRESS | EXPRESS + LICK |
|------------|-----------|-----|-----|------|---------|--------------|
| -0.20      | 1.4       | 1   | 17  | 5.9 ± 1.9 | 1      | 58          | 1.7 ± 0.5 |
| -0.20      | 2.2       | 0   | 5   | 0.0 ± 0.0 | 2      | 34          | 5.9 ± 1.9 |
| -0.20      | 3.0       | 0   | 0   | - -   | 0      | 21          | 0.0 ± 0.0 |
| -0.04      | 1.4       | 1   | 25  | 4.0 ± 1.3 | 3      | 54          | 5.6 ± 1.7 |
| -0.04      | 2.2       | 1   | 19  | 5.3 ± 1.7 | 2      | 70          | 2.9 ± 0.9 |
| -0.04      | 3.0       | 0   | 1   | 0.0 ± 0.0 | 0      | 30          | 0.0 ± 0.0 |
| +0.12      | 1.4       | 3   | 32  | 9.4 ± 3.0 | 7      | 48          | 14.6 ± 5.7 |
| +0.12      | 2.2       | 2   | 22  | 9.1 ± 3.1 | 6      | 46          | 13.0 ± 5.6 |
| +0.12      | 3.0       | 0   | 14  | 0.0 ± 0.0 | 2      | 36          | 5.6 ± 1.8 |
natural consequence of the planet formation mechanism around intermediate-mass stars.

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Table A.1. Radial velocity variations of HIP 8541

| JD - 2450000 | RV (m s\(^{-1}\)) | error (m s\(^{-1}\)) | Instrument |
|--------------|-------------------|----------------------|------------|
| 5457.7875    | -136.5            | 5.1                  | FEROS      |
| 6099.9286    | 59.6              | 4.9                  | FEROS      |
| 6110.8570    | 41.3              | 3.8                  | FEROS      |
| 6160.8413    | 25.2              | 3.5                  | FEROS      |
| 6230.6666    | 23.2              | 4.1                  | FEROS      |
| 6241.7042    | 23.2              | 3.8                  | FEROS      |
| 6251.7343    | 24.4              | 2.9                  | FEROS      |
| 6321.5772    | 1.4               | 4.2                  | FEROS      |
| 6565.7347    | -61.8             | 4.7                  | FEROS      |
| 6533.8456    | 78.4              | 5.1                  | CHIRON     |
| 6823.9189    | 2.9               | 5.1                  | CHIRON     |
| 6836.8384    | 17.3              | 5.1                  | CHIRON     |
| 6850.7623    | 0.6               | 4.8                  | CHIRON     |
| 6882.7614    | -0.6              | 4.0                  | CHIRON     |
| 6909.8364    | -15.4             | 4.0                  | CHIRON     |
| 6939.5587    | -26.2             | 4.1                  | CHIRON     |
| 6958.5726    | -30.7             | 4.3                  | CHIRON     |
| 6972.6441    | -25.9             | 4.4                  | CHIRON     |
| 6993.5329    | -37.6             | 3.6                  | CHIRON     |
| 7017.6540    | -11.2             | 4.0                  | CHIRON     |
| 7060.5258    | -39.9             | 4.3                  | CHIRON     |
| 7070.5331    | -9.6              | 4.7                  | CHIRON     |
| 7080.5042    | -25.0             | 6.6                  | CHIRON     |
| 7163.9265    | -17.9             | 6.0                  | CHIRON     |
| 7192.8795    | -14.2             | 4.3                  | CHIRON     |
| 7253.7358    | -0.3              | 4.9                  | CHIRON     |
| 7273.8077    | 10.0              | 3.9                  | CHIRON     |
| 7284.8938    | 20.1              | 4.9                  | CHIRON     |
| 7286.8216    | 32.6              | 5.2                  | CHIRON     |
| 7293.7664    | 27.6              | 4.6                  | CHIRON     |
| 7311.7297    | 25.8              | 3.9                  | CHIRON     |
| 7332.6564    | 39.3              | 3.8                  | CHIRON     |
| 5138.1360    | -53.1             | 1.7                  | UCLES      |
| 5496.1501    | -94.2             | 1.8                  | UCLES      |
| 5525.9950    | -83.6             | 1.8                  | UCLES      |
| 5880.0887    | 11.4              | 2.3                  | UCLES      |
| 5969.9464    | 44.3              | 2.3                  | UCLES      |
| 6527.2141    | 0.00              | 2.2                  | UCLES      |

Table A.2. Radial velocity variations of HIP 74890

| JD - 2450000 | RV (m s\(^{-1}\)) | error (m s\(^{-1}\)) | Instrument |
|--------------|-------------------|----------------------|------------|
| 5317.7161    | 43.8              | 5.3                  | FEROS      |
| 5336.8361    | 39.7              | 4.4                  | FEROS      |
| 5379.7325    | 41.7              | 3.9                  | FEROS      |
| 5428.5941    | 41.8              | 4.9                  | FEROS      |
| 5729.7413    | 68.9              | 4.8                  | FEROS      |
| 5744.6796    | 82.7              | 5.1                  | FEROS      |
| 5793.6145    | 59.0              | 6.2                  | FEROS      |
| 6047.6958    | -12.2             | 2.7                  | FEROS      |
| 6056.6979    | -31.1             | 2.9                  | FEROS      |
| 6066.6960    | -24.8             | 3.8                  | FEROS      |
| 6099.6861    | -21.7             | 3.5                  | FEROS      |
| 6110.6576    | -17.6             | 4.2                  | FEROS      |
| 6140.6536    | -28.7             | 4.9                  | FEROS      |
| 6321.8844    | -28.2             | 4.0                  | FEROS      |
| 6342.9030    | -16.0             | 3.8                  | FEROS      |
| 6412.6527    | -10.4             | 3.0                  | FEROS      |
| 7114.8393    | -102.5            | 4.2                  | FEROS      |
| 7174.5725    | -84.3             | 5.2                  | FEROS      |
| 4869.2727    | 158.3             | 2.4                  | UCLES      |
| 5381.0725    | 27.9              | 1.9                  | UCLES      |
| 5707.0809    | 77.6              | 4.6                  | UCLES      |
| 5969.2830    | 22.7              | 1.5                  | UCLES      |
| 5994.1579    | 5.6               | 2.0                  | UCLES      |
| 6052.0874    | 24.0              | 3.6                  | UCLES      |
| 6088.9942    | -22.0             | 1.7                  | UCLES      |
| 6344.2382    | -13.0             | 1.9                  | UCLES      |
| 6375.2713    | -0.0              | 1.9                  | UCLES      |
| 6400.1449    | 0.0               | 1.7                  | UCLES      |
| 6494.9152    | 1.3               | 2.0                  | UCLES      |
| 6529.9054    | -2.3              | 2.4                  | UCLES      |
| 6747.1435    | -37.8             | 1.6                  | UCLES      |

Appendix A: Radial velocity tables.
### Table A.3. Radial velocity variations of HIP 84056

| JD - 2450000 | RV (m s\(^{-1}\)) | error (m s\(^{-1}\)) | Instrument |
|--------------|-----------------|-----------------|------------|
| 5379.7813    | -59.2            | 3.4             | FEROS      |
| 5428.6445    | -44.2            | 4.0             | FEROS      |
| 5457.5635    | -49.2            | 2.6             | FEROS      |
| 5470.5498    | -42.7            | 11.2            | FEROS      |
| 5744.7607    | 38.5             | 5.6             | FEROS      |
| 5786.6509    | 33.6             | 3.9             | FEROS      |
| 6047.7637    | -2.7             | 7.1             | FEROS      |
| 6056.7446    | -9.7             | 4.4             | FEROS      |
| 6066.7539    | -16.1            | 5.3             | FEROS      |
| 6099.7607    | -20.4            | 5.0             | FEROS      |
| 6160.6299    | -20.0            | 3.4             | FEROS      |
| 6412.8618    | 17.7             | 3.7             | FEROS      |
| 6431.7646    | 27.8             | 5.9             | FEROS      |
| 6472.6177    | 31.2             | 3.5             | FEROS      |
| 6472.6514    | 9.1              | 4.0             | FEROS      |
| 6472.6346    | 10.8             | 3.5             | FEROS      |
| 6472.7095    | 16.5             | 4.3             | FEROS      |
| 6472.7666    | 24.6             | 3.4             | FEROS      |
| 6565.5210    | 54.4             | 4.7             | FEROS      |
| 6722.8143    | 34.2             | 3.5             | CHIRON     |
| 6742.7472    | 43.1             | 3.5             | CHIRON     |
| 6743.7859    | 36.2             | 4.3             | CHIRON     |
| 6769.7072    | 37.5             | 3.5             | CHIRON     |
| 6785.7443    | 46.1             | 3.7             | CHIRON     |
| 6804.6654    | 20.6             | 4.3             | CHIRON     |
| 6822.6781    | 9.5              | 5.5             | CHIRON     |
| 6839.5918    | 14.2             | 3.7             | CHIRON     |
| 6885.5857    | -14.5            | 4.7             | CHIRON     |
| 6904.5370    | -16.0            | 5.3             | CHIRON     |
| 6919.5493    | -22.6            | 3.8             | CHIRON     |
| 6928.5084    | -18.4            | 4.0             | CHIRON     |
| 6929.5103    | -17.3            | 3.8             | CHIRON     |
| 6937.5205    | -28.3            | 4.1             | CHIRON     |
| 6944.4897    | -14.3            | 4.2             | CHIRON     |
| 6954.4887    | -28.4            | 4.1             | CHIRON     |
| 7088.8135    | -18.5            | 3.8             | CHIRON     |
| 7124.7610    | -29.7            | 4.0             | CHIRON     |
| 7145.9299    | -26.9            | 4.5             | CHIRON     |
| 7166.6458    | -15.0            | 3.9             | CHIRON     |
| 7177.7871    | -19.7            | 5.1             | CHIRON     |
| 7207.6342    | -13.4            | 4.6             | CHIRON     |

### Table A.4. Radial velocity variations of HIP 95124

| JD - 2450000 | RV (m s\(^{-1}\)) | error (m s\(^{-1}\)) | Instrument |
|--------------|-----------------|-----------------|------------|
| 5379.8357    | -1.0            | 5.1             | FEROS      |
| 5457.6545    | 16.4            | 4.5             | FEROS      |
| 5744.8034    | -19.8           | 2.7             | FEROS      |
| 5786.7273    | -43.6           | 3.5             | FEROS      |
| 5793.7489    | -39.7           | 4.6             | FEROS      |
| 6047.8077    | 50.0            | 3.6             | FEROS      |
| 6056.7627    | 40.6            | 3.9             | FEROS      |
| 6066.7758    | 44.6            | 3.9             | FEROS      |
| 6110.7261    | 47.6            | 2.3             | FEROS      |
| 6110.7330    | 48.0            | 1.9             | FEROS      |
| 6160.7445    | 49.5            | 2.3             | FEROS      |
| 6160.6791    | 35.5            | 3.9             | FEROS      |
| 6241.5101    | 6.3             | 4.5             | FEROS      |
| 6431.8159    | -45.1           | 4.1             | FEROS      |
| 6472.7252    | -31.3           | 3.6             | FEROS      |
| 6472.7816    | -31.2           | 2.8             | FEROS      |
| 6472.7947    | -32.6           | 2.6             | FEROS      |
| 6472.8171    | -45.8           | 2.7             | FEROS      |
| 6472.8474    | -39.6           | 2.4             | FEROS      |
| 6565.5720    | -8.6            | 3.7             | FEROS      |
| 6895.5348    | -4.7            | 4.1             | CHIRON     |
| 6909.6056    | -6.3            | 3.9             | CHIRON     |
| 6911.5434    | -15.1           | 5.2             | CHIRON     |
| 6920.5681    | -11.2           | 3.9             | CHIRON     |
| 6921.5119    | -19.9           | 4.1             | CHIRON     |
| 6926.5602    | -15.8           | 3.8             | CHIRON     |
| 6936.5852    | -16.0           | 4.6             | CHIRON     |
| 6945.4849    | -12.0           | 6.9             | CHIRON     |
| 6976.5018    | -26.2           | 4.2             | CHIRON     |
| 7088.8888    | 27.0            | 4.1             | CHIRON     |
| 7099.8966    | 18.1            | 5.2             | CHIRON     |
| 5139.8852    | 4.7             | 4.9             | UCLES      |
| 5396.9380    | -15.2           | 4.2             | UCLES      |
| 6494.1188    | -14.2           | 2.3             | UCLES      |
| 6528.9451    | 0.0             | 2.5             | UCLES      |
| 6747.2858    | 26.5            | 2.2             | UCLES      |