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Confirming the Metal-Rich Nature of Stars with Giant Planets

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Abstract.

With the goal of confirming the metallicity "excess" observed in stars with planetary mass companions, we have conducted a high-precision spectroscopic study of a "comparison" sample of dwarfs included in the CORALIE extra-solar planet survey (Santos, Israelian, & Mayor 2001). The targets were chosen following two basic criteria: they make part of a limited volume and they do not present the signature of a planetary host companion. The spectroscopic analysis, done using the very same technique as previous works on the metallicity of stars with planets, permitted a direct and non-biased comparison of the samples. The results have revealed that metallicity plays an impressive role on the giant planet formation. The chemical composition of the molecular cloud is probably the key parameter to form giant planets. Some evidences exist, however, showing the possibility of accretion of matter in the stellar outer convective zone. These conclusions impose serious constraints on the planetary systems formation and evolution models.

1. Introduction

Following the discovery in 1995 of the planet orbiting 51 Peg (Mayor & Queloz 1995), we have witnessed a complete revolution in the field of extra-solar planets. Almost 70 other exo-planets were unveiled since then, and the most striking and interesting result to date is the "simple" fact that the discovered systems do not have much in common with our own Solar System (see e.g. Udry et al. 2001). The new results are showing that planet formation is not as simple as we thought. In particular, following the traditional paradigm for planetary formation, the currently found exo-planets were not even supposed to exist. The direct implication of this results is the strong need to reconsider theories of planetary formation and evolution.

To achieve this important goal we need observational constraints. These can be found by looking at the planetary orbital characteristics, like the distribution of eccentricities and periods, or to the distribution of planetary masses (e.g. Udry et al. 2001; Mayor & Santos 2001). But further evidences seem to be coming from the planet host stars themselves, namely by the fact that stars

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Table 1. Derived abundances and atmospheric parameters for the 7 planet-hosts not included in the study of SIM01.

HD Number	T_{eff} (K)	$\log g$ ($\mathrm{cm\,s^{-2}}$)	ξ_t ($\mathrm{km\,s^{-1}}$)	[Fe/H]	Reference
HD 106252	5890	4.40	1.06	−0.01	This paper
HD 141937	5925	4.62	1.16	0.11	This paper
HD 160691	5820	4.44	1.23	0.33	This paper
HD 178911 B	5650	4.65	0.85	0.28	Zucker et al. (2001)
HD 179949	6235	4.41	1.38	0.21	This paper
HD 195019	5830	4.34	1.24	0.09	This paper
HD 213240	5975	4.32	1.30	0.16	Santos et al. (2001)

with planets are particularly metal-rich (Gonzalez 1998; Santos, Israelian & Mayor 2001 – hereafter SIM01).

The fact that stars with planets[1] are particularly metal-rich has been shaded until recently in one point: to compare the metallicity of stars with planets with the metallicity of stars "without" planets, authors were restricted to published metallicity studies of volume limited samples of dwarfs in the solar neighborhood (mainly the one from Favata et al. 1997). This has a few inconvenients, the most important being that the metallicities for the "star-with-planet" and the Favata et al. sample were determined using different sources for the atmospheric parameters (spectroscopic vs. colours) – see e.g. Santos, Israelian & Mayor (2000) – hereafter SIM00. This may introduce systematic errors, and one could expect that the difference between the two samples was simply reflecting a bias.

With the goal of settling down the question about the high metallicity content of stars with planets, we have recently conducted (SIM01) a spectroscopic study of a volume limited sample of 43 stars included in the CORALIE planet search programme (Udry et al. 2000)[2], and for which the radial-velocity seems to be constant over a large time interval. In SIM01 we have shown that the currently known stars with giant planets are in average more metal-rich than "field stars" for which there is no radial-velocity signature of planets. Furthermore, the results exclude with great significance a "pollution" scenario. In this paper we will review these results, adding 7 more stars to the planet-host sample, and showing that the new points do confirm the results presented in SIM01.

2. The Data

The technique and analysis, as well as the data, were presented and discussed in SIM00 and SIM01. In the meanwhile we have obtained spectra for 6 stars

[1]Here we are referring to the now known extra-solar planetary host stars, orbited by Jupiter-like planets in relatively short period orbits, when compared to the giant planets in our Solar System.

[2]See also http://obswww.unige.ch/~udry/planet/planet.html

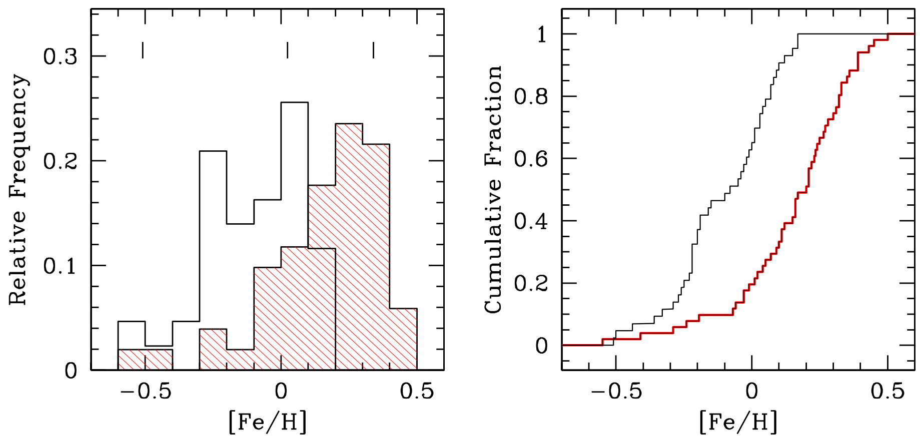

Figure 1. *Left*: [Fe/H] distribution of stars with planets (shaded histogram) compared with the same distribution of field dwarfs in the solar neighborhood (open histogram). The vertical lines represent stars with brown dwarf candidate companions having minimum masses between 10 and 20 M_{Jup}. *Right*: The cumulative functions of both samples. A Kolmogorov-Smirnov test shows the probability of the stars' being part of the same sample is around 10^{-8}.

with planets not included in previous studies[3]. The results of the spectroscopic analysis for those 6 "new" objects are presented in the table. Another planet host (HD 178911 B), not analyzed by us but by someone from the group (using the same technique, line-lists and model atmospheres) is also included in the table (with the correct reference). Errors were discussed in SIM01.

3. The Metallicity Excess

In Fig. 1 (left) we can see a comparison between the [Fe/H] distribution of our volume limited sample of field dwarfs without detected planetary mass companions, and the same distribution for the stars with planets. There is a remarkable difference between both distribution, as can be seen from their cumulative functions – Fig. 1 (right).

The plots leave no doubts: stars with planets, or at least with planets similar to the ones we are finding today, are clearly more metal rich that stars without planetary companions. Even if we look just at the table, all but one of the 7 planet hosts with "new" [Fe/H] measurements have metallicity higher than solar. The mean [Fe/H] difference between both samples is around 0.25 dex. As discussed in SIM01, given the uniformity of the analysis and the absence of observational biases in both samples, these results represent a real trend.

[3]Both using the CORALIE spectrograph, at the 1.2-m Euler Swiss telescope, at La Silla (ESO), Chile, and the UES spectrograph, at the William Herschel Telescope, at La Palma, Canary Islands.

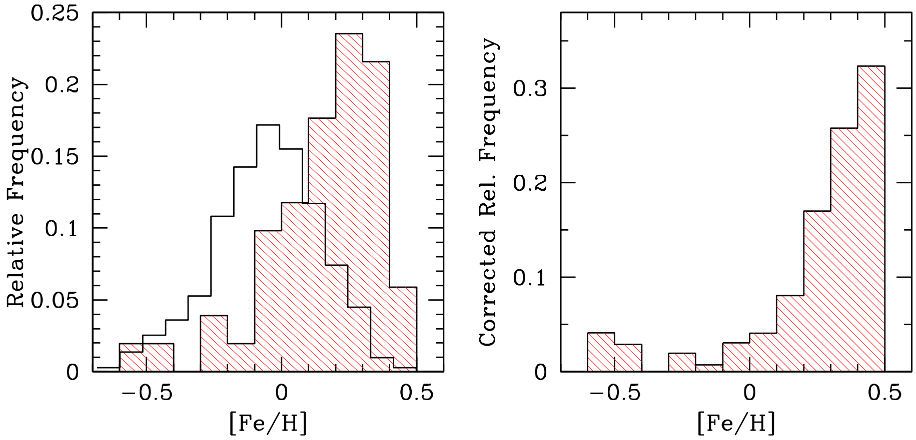

Figure 2. *Left*: metallicity distribution of stars with planets (dashed histogram) compared with the distribution of a large volume limited sample of field dwarfs (empty histogram) – see SIM01 for more details; *right*: correcting the distribution of stars with planets from the same distribution for stars in the volume-limited sample results in a even more steep rise of the planet host star distribution as a function of [Fe/H].

In the figure, stars with low-mass brown-dwarf companions ($10\,\mathrm{M_{Jup}} < \mathrm{M_2}\sin i < 17\,\mathrm{M_{Jup}}$) are denoted by the vertical lines. No conclusion can be taken at this moment concerning these cases, but a large dispersion seems to be present.

More interesting conclusions can be taken by looking at the shape of the distribution of stars with planets alone – Fig. 2 (left). As can be seen from the plot, this distribution is rising with [Fe/H], up to a value of $\sim$0.4, after which we see a sharp cutoff. This cutoff suggests that we may be looking at the approximate limit on the metallicity of the stars in the solar neighborhood. On the other hand, the steep rise cannot be explained by any sampling bias.

The trend is even more clear if we correct the distribution for the fact that the peak in the metallicity distribution for stars in the solar neighborhood is around solar metallicity: it is more easy to find a star with [Fe/H]=0 than with [Fe/H]=0.5. The result, presented in Fig. 2 (right), leaves no doubts: the probability of finding a planet host is a strong function of its metallicity. As discussed in SIM01, this cannot be the result of any observational bias, and is just probably telling us that the probability of forming a giant planet depends strongly on the metallicity of the gas that gave origin to the star and planetary system. And although it is unwise to take any strong conclusions based on one point, it is worth of note that our own Sun is in the "metal-poor" tail of the planet hosts [Fe/H] distribution!

Finally, the small "bump" seen for low metallicities in the corrected distribution is clearly not statistically significant, since only one planet host per bin exists in this region of the plot. Only the addition of more data will permit to say more on this point. If it remains with better statistics, or with the discovery of very low mass companions (a few earth masses) it could suggest e.g. that the

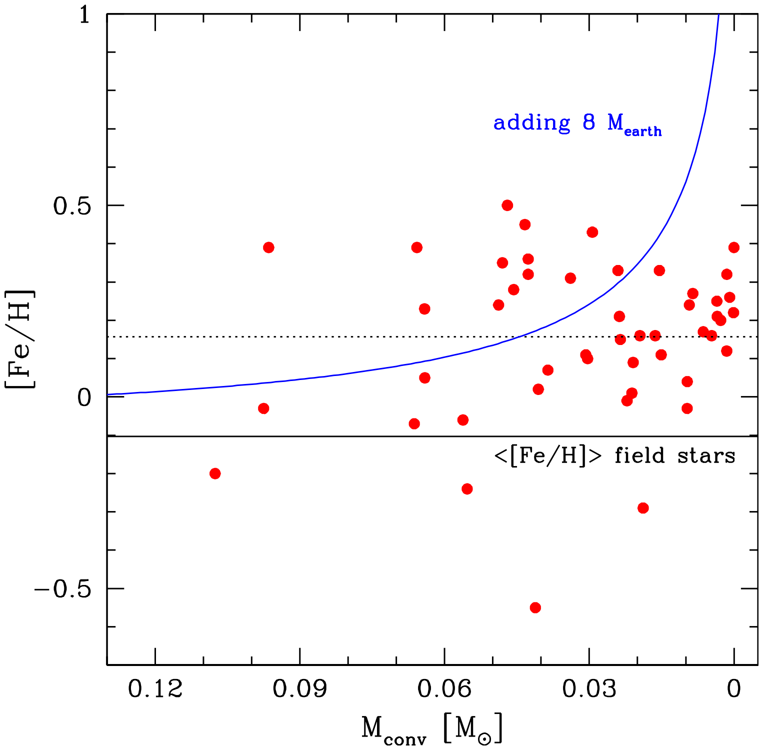

Figure 3. Metallicity against convective envelope mass for stars with planets (dots). The [Fe/H]=constant line represents the mean [Fe/H] for the non-planet hosts stars of Figure 1. The curved line represents the result of adding 8 earth masses of iron to the convective envelope of stars having an initial metallicity equal to the non-planet hosts mean [Fe/H]. The resulting trend has no relation with the distribution of the stars with planets.

current trend is valid only for the giant planets found today, and that very low mass planetary companions can be easily formed even in low metallicity environments. Note that the planet around HD 6434, the lower metallicity planet host in the histograms (SIM01), has a minimum mass below 0.5 M_{Jup}.

4. The "Primordial" Origin

Two different interpretations have been given to the [Fe/H] "excess" observed for stars with planets. One suggests that the high metal content is the result of the accretion of planets and/or planetary material into the star (e.g. Gonzalez 1998). Another, simply states that the planetary formation mechanism is dependent on the metallicity of the proto-planetary disk: according to the "traditional" view, a gas giant planet is formed by runaway accretion of gas by a ∼10 earth masses planetesimal. The higher the metallicity (and thus the number of dust particles) the faster a planetesimal can grow, and the higher the probability of forming a giant planet before the gas in the disk dissipates.

There are multiple ways of deciding between the two scenarios (see discussion in e.g. SIM01). Probably the most clear and strong argument is based on stellar internal structure, in particular on the fact that material falling into a star's surface would induce a different increase in [Fe/H] depending on the stellar mass, i.e. on the depth of its convective envelope (where mixing can occur). However, the data shows no such trend (see Fig. 3). In particular, a quick look at the plot indicates that the upper envelope of the points is quite constant. A similar conclusion was also recently taken by Pinsonneault et al. (2001) that showed that even non-standard models of convection and diffusion cannot explain the lack of a trend and sustain "pollution" as the source of the high-[Fe/H].

Together with the fact that evolved stars with planets also show high-metallicity values, and that it seems to be quite difficult to explain the sharp cutoff in the metallicity distribution of stars with planets using simple pollution models (SIM01), the facts presented here strongly suggest a "primordial origin" to the high-metal content of stars with giant planets. This result implies that the metallicity is a key parameter controlling planet formation and evolution, and may have enormous implications on theoretical models.

5. Metallicity and Orbital Parameters

Given that we already have about 55 extra-solar planet hosts with high-precision and uniform metallicity determinations, we can start to think about looking for possible trends in [Fe/H] with planetary mass, semi-major axis or period, and eccentricity.

Gonzalez (1998) and Queloz et al. (2000) have shown evidences that stars with short-period planets (i.e. small semi-major axes) may be particularly metal-rich, even amongst the planetary hosts. The number of planets that were known by that time was, however, not enough to arrive at a definitive conclusion.

Recent analysis (SIM01) seems in fact to discard any special trend. The result, also shown here in Fig. 4 (now including the 7 planet hosts presented in the table and not included in the study of SIM01), shows a small tendency for short period systems to have higher metallicity (see the cumulative functions). However, this tendency is clearly not significant; the Kolmogorov-Smirnov probability that both samples belong to the same population is $\sim$0.7.

In Fig. 4 the multi-planetary systems, not included in the histograms, are denoted by the vertical lines[4]. Although we do not have many points, the current results also do not show any strong trend (although they all seem to be particularly metal-rich).

The same situation can be found concerning other orbital parameters, like the eccentricity or planetary mass. However, current results do not discard that e.g. when much lighter planets or when systems more similar to the Solar System are found some trend may appear (see also discussion in section 3).

[4] These include the systems around υ And (Butler et al. 1999), HD 83443 (Mayor et al. 2001a), HD 168443 (Udry et al. 2001), HD 82943 (Mayor et al. 2001b), and 47 UMa (Fischer et al. 2001)

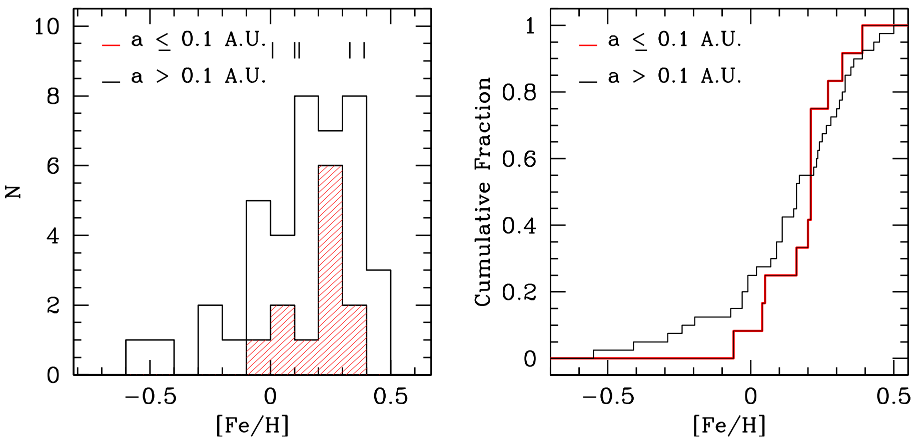

Figure 4. *Left*: [Fe/H] distributions for planets orbiting at distances shorter and higher than 0.1 AU from their host stars (the hashed and open bars, respectively). *Right*: cumulative functions of both distributions. A Kolmogorov-Smirnov test gives a probability of $\sim$0.7 that both samples make part of the same distribution.

6. HD 82943: a Case of Pollution

Although the results presented above seem to rule out pollution as the key parameter inducing the high metallicity of planet hosts stars, some evidences of pollution have been discussed in the literature (e.g. Gonzalez 1998; Laws & Gonzalez 2001). Perhaps the strongest evidence for such phenomena came recently from the detection of an "anomalous" ^{6}Li/^{7}Li ratio on the star HD 82943, a late F dwarf known to have two orbiting planets (Israelian et al. 2001).

The rare ^{6}Li isotope represents an unique way of looking for traces of "pollution". So far, this isotope had been detected in only a few metal-poor halo and disc stars, but never with a high level of confidence in any metal-rich or even solar-metallicity star. Standard models of stellar evolution predict that ^{6}Li nuclei are efficiently destroyed during the early evolution of solar-type stars and disappear from their atmospheres within a few million years. Planets, however, do not reach high enough temperatures to burn ^{6}Li nuclei, and fully preserve their primordial content of this isotope. A planet engulfed by its parent star would boost the star's atmospheric abundance of ^{6}Li.

In fact, planet engulfment following e.g. planet-planet (Rasio & Ford 1996) or planet-disk (Goldreich & Tremaine 1980) interactions seems to be the only convincing and the less speculative way of explaining the presence of this isotope in the atmosphere of HD 82943.

It is important to note, however, that the quantity of material we need to add to the atmosphere of HD 82943 in order to explain the lithium isotopic ratio would not be able to change the [Fe/H] of the star by more than a few cents of a dex. Furthermore, it it not clear how often this kind of events occur. In this context we would like to call attention to the contribution by Garcia Lopez et al. (2001, this book). In any case, the conclusions presented above, supporting

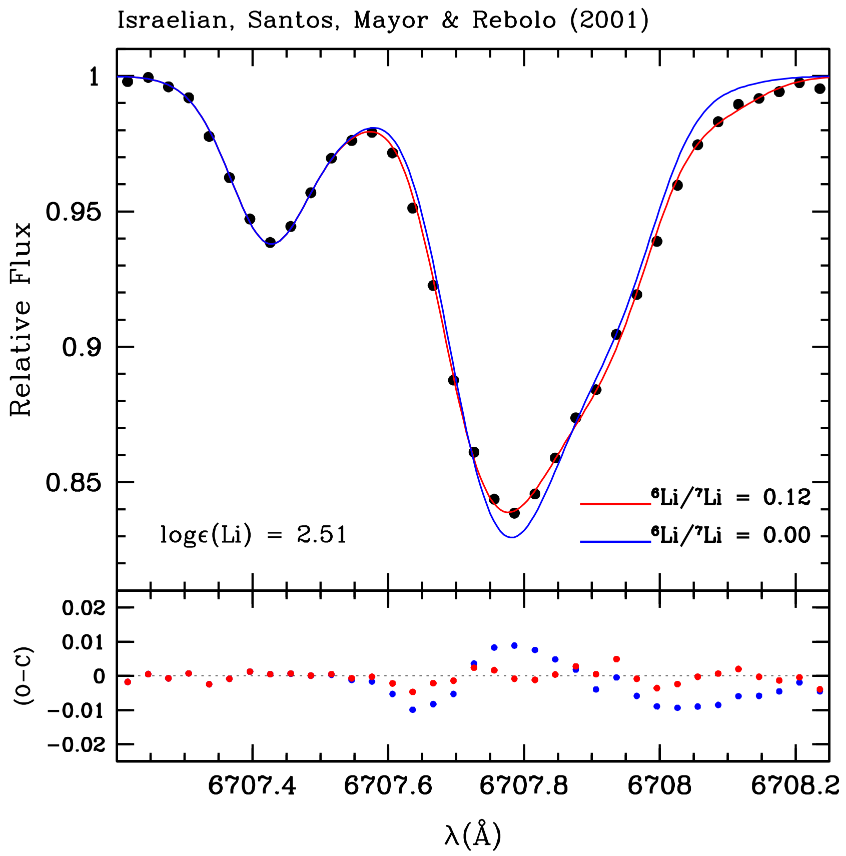

Figure 5. ^{6}Li signature on the spectrum of HD 82943 (dots) and two spectral synthesis, one with no ^{6}Li and the other with a ^{6}Li/^{7}Li ratio of 0.12 (compatible with the meteoritic value). The O-C residuals of both fits are shown.

a "primordial" source for the high [Fe/H] of planet host stars are not dependent on this cases of "pollution".

Note also that we are referring to the fall of planets or planetary material after the star has reached the main-sequence phase and fully developed a convective envelope; if engulfment happens before that, all planetary material will be deeply mixed, and no traces of pollution might be found. It is interesting to note that the whole giant-planetary formation phase[5] must take place when a disk of gas (and debris) is present. Massive gas disks may not exist at all when a star like the Sun reaches the main-sequence phase (inner disks seem to disappear after ~10 Myr – e.g. Haisch, Lada, & Lada – although recent work by Thi et al. 2001 suggests that gas disks, associated with debris disks, and that are massive enough to form "jupiters", may survive up to 30 Myr). Thus, all the "massive" infall that would be capable of changing the measured elemental

[5]This is probably also true for all the action concerning hypothetical planet/planetary material engulfment.

abundances if the star were already at the main-sequence might simply occur too early, explaining why we do not see strong traces of pollution (in particular, concerning iron).

Although a bit speculative, the fact that no significant "pollution" is seen can be used as an evidence that disks life-times are in general shorter than pre-main-sequence duration, if we suppose that planets (in particular planetary building blocks) are in fact engulfed by the star at some stage (e.g. Murray et al. 1998). This fact, if confirmed, could deepen the problem concerning the planetary formation time-scales.

7. Conclusions

The results presented in this paper, most of them based and already presented in SIM01 and Israelian et al. (2001), can be summarized as follows:

- The currently known stars with planets are substantially metal-rich when compared with non-planetary host dwarfs. The mean difference in [Fe/H] is $\sim$0.25 dex and is clearly significant.
- The shape of the metallicity distribution of stars with planets has a very clear rise with [Fe/H]. This indicates that the probability of finding (and forming) a planet is a strong function of [Fe/H].
- "Pollution" does not seem to play an important role in determining the high metal content of the planet host stars. The excess metallicity seems to have a "primordial" origin.
- Some traces of pollution seem to exist concerning light-element abundances, and in particular the lithium isotopic ratio. The frequency of such events is, however, still not known.
- An analysis of the planetary orbital parameters (a, $m_2 \sin i$, and e) does not reveal any clear trends with [Fe/H].

These results can be basically summarized in one sentence: planetary formation and/or evolution, or at least the formation of the planetary systems we are currently detecting, seems to be extremely dependent and sensitive on the metallicity of the cloud that gives origin to the star/planet system. Given the strong observational constraints this work is giving, it would be interesting to compare the current results with models in order to better understand exactly why this is so.

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