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Evolved stars suggest an external origin of the enhanced metallicity in planet-hosting stars

L. Pasquini[1], M. P. Döllinger[1,4], A. Weiss[4], L. Girardi[3], C. Chavero[5,6], A. P. Hatzes[2], L. da Silva[6], and J. Setiawan[7]

[1] European Southern Observatory, Garching bei München, Germany
   e-mail: lpasquin@eso.org
[2] Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany
[3] INAF – Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[4] Max-Planck-Institut für Astrophysik, Garching bei München, Germany
[5] Instituto de Astrofísica de Canarias, 38200, La Laguna, Tenerife, Spain
[6] Observatório Nacional/MCT, 20921-400 Rio de Janeiro, Brasil
[7] Max Planck Institute Für Astronomie, Heidelberg, Germany

ABSTRACT

Aims. Exo-planets are preferentially found around high metallicity main sequence stars. We investigate whether evolved stars share this property, and its implications for planet formation.
Methods. Statistical tools and the basic concepts of stellar evolution theory are applied to published results as well as our own radial velocity and chemical analyses of evolved stars.
Results. We show that the metal distributions of planet-hosting (P-H) dwarfs and giants are different, and that the latter do not favor metal-rich systems. Rather, these stars follow the same age-metalicity relation as the giants without planets in our sample. The straightforward explanation is to attribute the difference between dwarfs and giants to the much larger masses of giants' convective envelopes. If the metal excess on the main sequence is due to pollution, the effects of dilution explain why this is not observed in evolved stars.
Conclusions. Although we cannot exclude other explanations, the lack of any preference for metal-rich systems among P-H giants could be a strong indication of the accretion of metal-rich material. We discuss further tests, as well as some predictions and consequences of this hypothesis.

Key words. stars: abundances – stars: evolution – stars: planetary systems

1. Introduction

Just a few years after the discovery of the first extra-solar planet (Mayor & Queloz 1995) it has become evident that giant planets are preferentially found around metal-rich solar type stars (e.g. Gonzalez 1997, 1998, 2001; Santos et al. 2000, 2001, 2003, 2004; Fischer & Valenti 2005). Subsequent studies have shown that this preference is real (e.g. not produced by spurious selection effects), and that planet-hosting (P-H) stars are on average about 0.25 dex more metal-rich than their counterparts (Santos et al. 2004, 2005). The immediate question, which is very relevant for the understanding of planet formation, is if this increased metallicity enhances planet formation, or if the high metallicity is caused instead by the presence of a planetary system.

In the first case, favored by the core-accretion scenario (Pollack et al. 1996), the stars should be overmetallic down to their center. This scenario proposes that a solid core grows via the accretion of planetesimals until it has sufficient mass to capture gas from the nebula to form an envelope. In this case, the planet formation depends strongly on dust content (Ida & Lin 2004).

In the second case the star was polluted by the debris of the planetary system and only the external layers were affected by this pollution (Laughlin & Adams 1997). This scenario is compatible with the gravitational instability mechanism: a gravitationally unstable region in a protoplanetary disk forms self-gravitating clumps of gas and dust within which the dust grains coagulate and sediment to form a central core (Boss 1997). Boss (2002) argues that the gravitational instability model should depend very weakly on metallicity, contrary to what is expected from the core accretion scenario.

The pollution scenario has been considered previously and several authors have investigated the dependence of metallicity on the effective temperature of P-H stars. Since the depth of the convective zone increases with lower mass along the main sequence, a trend with stellar temperature is expected. The effect, if present at all, is very small and this led most authors to conclude that an enhanced primordial metallicity of the host stars is favored (e.g. Santos 2005). The situation is however complicated because of additional mixing beyond the formal convective boundary, either due to thermohaline convection and "metallic fingers" (Vauclair 2004), or due to other effects that manifest in the lithium dip in open clusters (Murray et al. 2001).

A few groups have started surveys of evolved stars, G and K giants, to learn how planets form among more massive stars and to understand the radial velocity variability of these objects (Setiawan et al. 2003b, 2004; Sato et al. 2007). These surveys along with other observations led to the discovery of 10 exo-planets around giant stars. Several authors pointed out that planet-hosting giants are not preferentially metal-rich

systems (Sadakane et al. 2005; Schuler et al. 2005; Da Silva et al. 2006). The data published were few and sparse, precluding any further analysis.

2. Giants hosting planets

The 10 G and K P-H giants include HD 137759 (Frink et al. 2002), HD 47536 and HD 122430 (Setiawan et al. 2003a,b), HD 104985 (Sato et al. 2003), HD 222404 (Hatzes et al. 2003), HD 11977 (Setiawan et al. 2005), HD 13189 (Hatzes et al. 2005), β Gem (Hatzes et al. 2006), 4 UMa (Döllinger et al. 2007a), HD 28305 (Sato et al. 2007). One of the latest, 4 UMa, is part of a survey started 4 years ago at the Tautenburg observatory (Döllinger et al. 2007a–c); the details about the observations, analysis, and results can be found in the cited papers. In addition to 4 UMa, at least 4 other candidates are present in the Tautenburg survey (Döllinger et al. 2007c); adding these to the stars in the literature we have a total of 14 giants, for 10 of which all parameters have been derived in a homogeneous way.

The metallicity distribution for these 14 giants is shown in Fig. 1 together with the distribution of the P-H main sequence stars (small black dots; data from the Schneider catalogue). The two distributions have a similar shape, but the giant distribution is shifted by about 0.3 dex towards lower metallicity. A K-S test shows that the probability of both distributions belonging to the same population is around 10^{-4}. Systematic differences, such as due to the different metallicity scale adopted might be present, but they are certainly much smaller than the shift observed. However,

1) The giant survey is not explicitly biased towards metal-rich stars, while the search for planet around main sequence stars might be (Fischer et al. 2005). Santos et al. (2004) and Fischer & Valenti (2005) consider that the shift of 0.25 dex between P-H and not P-H dwarfs is real. Conversely, the distribution of P-H giants follows the general distribution for giants as seen in Fig. 2, which shows the age-metallicity distribution of the 130 giants analyzed by our group (da Silva et al. 2006; Döllinger et al. 2007b).

2) Giants do not posses short period planets, which would eventually have been swallowed by the expanding stellar envelope. Indeed, the shortest period for a planet around a giant is 198 days for HD 104985 (Sato et al. 2003). In Fig. 1 the dashed line represents the distribution of the main sequence P-H stars with periods longer than 180 days. Clearly, by selecting only the long period planets the metal distribution of the dwarfs does not change. We therefore conclude that there is a real difference in the metal distribution of main sequence and evolved P-H stars. Evolved P-H stars are 0.2–0.3 dex more metal-poor than main sequence P-H stars. Interestingly, this difference is similar to that observed between P-H and non-P-H main sequence stars.

3. Interpretation

There are at least three main differences between main sequence stars and giants:

1) On average giants have a somewhat higher mass than the main sequence stars surveyed for planets. Even considering that the determination of mass in giants suffers large uncertainties, the masses of planet-hosting giants vary between ~0.9 and ~3 $M_\odot$ (Da Silva et al. 2006; Döllinger et al. 2007b), while those of main sequence stars are between ~0.75 and ~1.5 $M_\odot$. Since the fraction of P-H giants is largely independent of metallicity, it is feasible that intermediate mass stars favor a planet formation
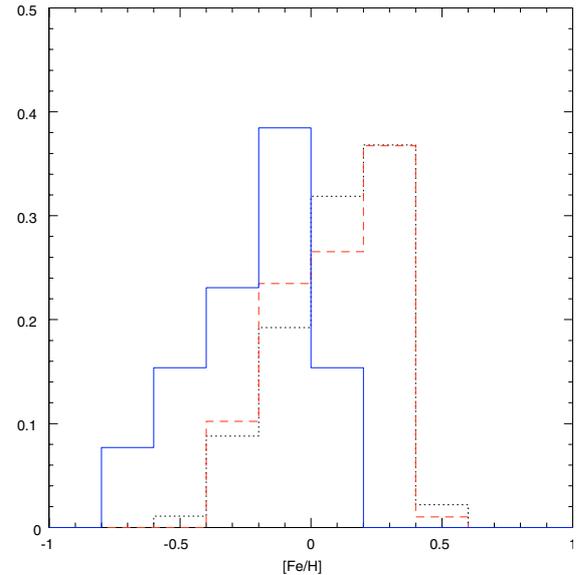

Fig. 1. Metal distribution for planet-hosting (P-H) giants (full line), P-H dwarfs with periods larger than 180 days (dashed line) and all P-H dwarfs (dotted). The giants show a distribution shifted to lower metallicity by about 0.2–0.3 dex with respect to the dwarfs.
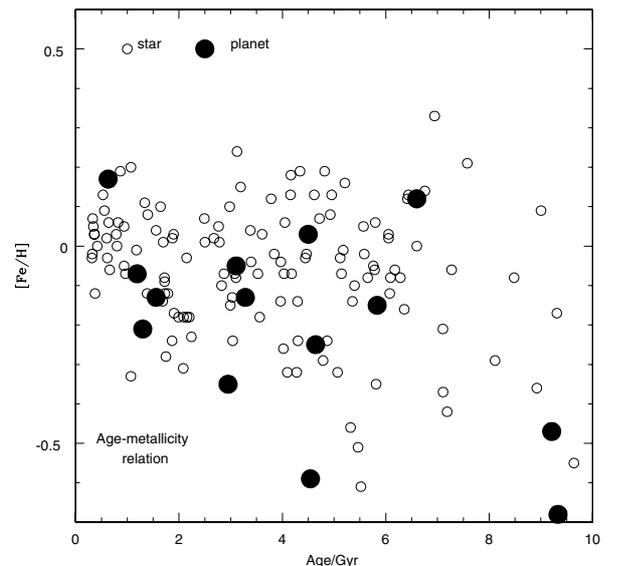

Fig. 2. Age-metallicity relationship for all giants belonging to the da Silva et al. (2006) and Döllinger et al. (2007b) samples and for the P-H giants, which closely follow the other stars.

mechanism, such as gravitational instability, which is independent of metallicity. One could speculate that such a mechanism is more efficient in more massive stars, which (likely) have more massive disks. The dependence of metallicity on stellar mass among main sequence P-H stars has already been investigated by Fischer & Valenti (2005) who derived fits to the mass-metallicity distribution of P-H and not P-H stars of their sample. Both fits have the same slope and, independent of stellar mass, P-H stars are more metal-rich than stars without planets. This result would therefore argue against the hypothesis that the planet formation mechanism changes significantly with the stellar mass. We notice, however, that the mass range covered by the Fischer and Valenti study is limited to 0.8–1.2 $M_\odot$, while by observing giants we cover a larger range of stellar mass.
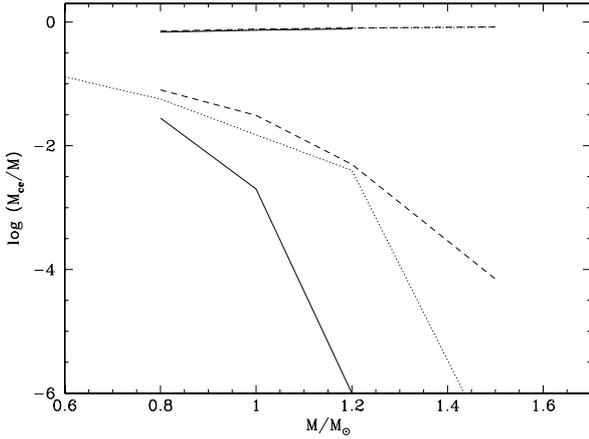
Fig. 3. Convective envelope mass M_{ce} (logarithmic scale; in units of stellar mass) for stars of varying mass and in two evolutionary phases. Shown are three metallicity cases: $Z = 0.005$ (solid lines), $Z = 0.017$ (dotted), and $Z = 0.026$ (dashed). The lower set of lines corresponds to main sequence, the upper to red giant models. The drastic enlargement of the convective mass during the RGB ascent is clearly visible. It is close to a factor ~50 for a solar-type star.

2) Giants have on average radii that are about 10 times larger than solar-type stars. If high metallicity favors the migration of planets towards short period systems, metal-rich stars have more short period planets than metal-poor stars. Since these planets are swallowed by the evolved star due to its large radius, those stars would be classified as P-H on the main sequence, and non-P-H when evolved.

The case of metal-dependent migration has been discussed, for example, in Santos et al. (2006): higher metallicity should result in a shorter timescale for inward migration. How effective this mechanism could be is however a matter of debate; Livio & Pringle (2003) find that a decrease in metallicity by a factor of 10 could slow down by at most a factor of 2 the timescale for migration. While these authors consider this negligible, Boss (2005) argues that this factor is enough to influence the observed trend between metallicity and P-H stars.

The metallicity distribution of Fig. 1 is very different for P-H giants and dwarfs with comparable long orbital periods. This indicates that the effects of migration, if present, cannot explain the different metal distribution of P-H dwarfs and giants.

We cannot exclude that several mechanisms are at work simultaneously and that they combine to produce the observed distribution. A dual formation scheme (one metal dependent, a second metal independent) has been proposed (see e.g. Matsuo et al. 2007). The metal-independent planet formation mechanism could be more effective for larger stellar masses and act therefore on giants much more than on main sequence stars.

3) The most likely explanation is related to the quantity that varies most between dwarfs and giants: the mass of the convective zone. While in the Sun the fraction of the solar mass in the convective envelope M_{ce} is ~0.022 $M_\odot$ (log $M_{ce} = -1.67$), when the star reaches its maximum depth along the RGB, this fraction is about 35 times higher, or almost 0.77 $M_\odot$ (log $M_{ce} = -0.11$). In general, when a 1 $M_\odot$ star becomes a K giant, its convective envelope is of the order of 0.7 $M_\odot$. If the high metallicity observed among main sequence stars was confined to the superficial layers, with a deepening convective envelope, this would be easily decreased to the primordial abundance of the star. In Fig. 3 we show the fractional mass (in logarithmic units) contained in the convective envelope of stars between 0.8 and 1.5 $M_\odot$, both
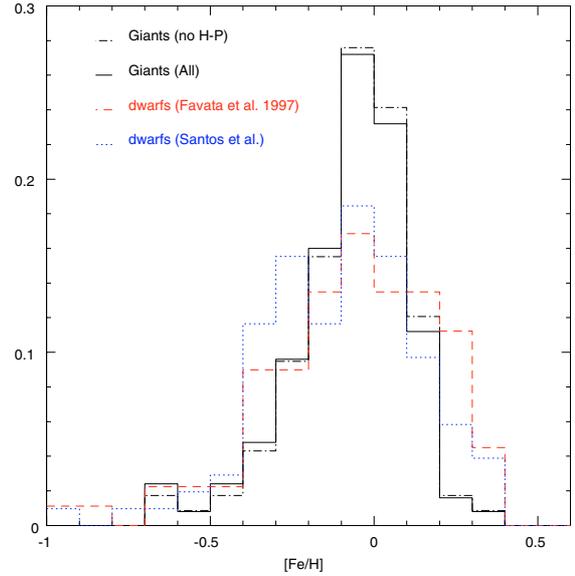

Fig. 4. Metal distribution for all the giants from the da Silva et al. (2006) and Döllinger et al. (2007b) sample for all stars (full line) and for not P-H giants (dashed-dotted line), for the volume limited sample of Favata et al. (1997, dashed) and Santos et al. (2004, 2005, points). An excess of metal-rich stars might be present among the dwarfs. To make such a comparison significant, a number of effects in the sample selection and in the analysis should be considered.

on the main sequence and on the red giant branch where the convective envelope has reached its deepest. This indicates the maximum dilution factor. Considering, for instance, an excess of 0.25 dex in [Fe/H] (Santos et al. 2005) in a solar star, that would become less than 1% in a giant star, a quantity which is beyond the actual detection capabilities in most observational cases.

As summarized in the introduction, pollution has been the subject of several investigations (Santos et al. 2005; Ecuvillon et al. 2006; Desidera et al. 2004, for binary systems), which did not find any evidence for it. Previous investigations, however, were restricted to a limited range of convective masses, while with giants we greatly enlarge this range. We also emphasize that the actual amount of envelope mass into which the accreted metals will be mixed on the main sequence is most likely not just the convective envelope, but the region into which thermohaline mixing reaches (Vauclair 2004), and this is determined mainly by molecular weight and not by the stellar mass. We have tested this effect on our own stellar models in the range of 0.6 to 0.9 $M_\odot$, finding that the total mass external to a layer with a given molecular weight is the same (within 10%), independent of the stellar mass. If this mixing is at work, a correlation between stellar metallicity and mass (or position on the main sequence) can therefore not be expected. The depleted solar Li abundance (Müller et al. 1975) clearly shows that the sun has suffered some form of extra mixing, as did stars in open clusters. The additional mass affected might be as much as 0.05 $M_\odot$, which is more than twice the present convective envelope mass, but still small if compared to the envelope mass of a giant.

Even if the observations of giants support the hypothesis that pollution is very important, more evidence is required to prove it. We need well controlled samples, in age, mass, and internal structure (e.g. if diffusion is at work). If the hypothesis of pollution is true, we expect an excess of metal-rich stars among main sequence stars with respect to an *equivalent* sample of giants. In Fig. 4 we show the metal distribution of the giants from da Silva et al. (2006) and Döllinger et al. (2007b) compared to the

distribution of a volume-limited sample of main sequence stars from Favata et al. (1997) and Santos et al. (2004, 2005). As far as the giants are concerned, we plot the distribution of the whole sample and the distribution of the non-P-H stars separately. No real difference can be discerned between the two giant distributions. The giant and dwarf distributions are also very similar, with the main sequence stars showing a (not significant) excess in the highest metallicity bins. The comparison between the giants and the Favata et al. (1997) results in particular suggests that the small excess of metal-rich dwarfs is almost perfectly compensated by an excess of solar-metallicity giants, which is exactly the signature we would expect from pollution. However this excess is mostly due to the coolest main sequence stars and other aspects, such as age distribution and galactic evaporation, should be taken into account to properly compare the data (Favata et al. 1997).

Any difference in the correlation between the presence of planets and metallicity should also become evident when observing stars on the hot and cool parts of the SGB, where the convective zone deepens by a factor 10–100 in a relatively short interval of magnitude and time. Fischer & Valenti (2005) searched for a slope in the metallicity distribution of subgiants but did not find any. Murray et al. (2001), however, did find evidence for lower metallicity in Hertzsprung gap stars with respect to their main sequence sample. A dedicated study should be devoted to this point.

Open clusters and associations might be optimal sites for investigating the effects of pollution. In the presence of P-H stars, a direct measurement should reveal an excess of metallicity, or at least a larger spread among the main sequence stars, but not among the giants belonging to the same cluster. This investigation could be also extended to the cooler part of the main sequence where the convective zone is significantly deeper than for solar-type stars. Most interesting could be a search for "outliers": proper motions and/or radial velocity open clusters members with discrepant (higher) metallicity. This could be an efficient way of identifying P-H candidates in open clusters and associations and to test the pollution hypothesis.

4. Conclusions

By enlarging the number of known giants hosting exoplanets, it has been possible to establish that their metallicity distribution is very different from that of planet-hosting main sequence stars. Giants hosting exoplanets do not favor high metallicity objects, but follow the age-metallicity distribution observed for all stars surveyed.

The interpretation of the data is not straightforward: a scenario which includes strong differences in planet formation with stellar mass and possibly planet migration is plausible, but the most immediate explanation is that the high metallicity observed among main sequence stars is due to pollution of their atmospheres. The metal excess produced by this pollution, while visible in the thin atmospheres of solar-like stars, is completely diluted in the extended, massive envelopes of the giants. This interpretation is in apparent contrast with results on main sequence stars obtained by several groups (Fischer & Valenti 2005; Ecuvillon et al. 2006, among others), which favor the primordial scenario, where stars are born in high metallicity clouds. We

believe that the possible explanation of this discrepancy is that the effects of pollution on the main sequence are small and difficult to detect. The fact that Fischer & Valenti (2005) do not find any evidence for dilution among a subsample of subgiants is of greater concern. The subgiants analyzed by Fischer & Valenti (2005) belong to the survey of 156 subgiants (evolved A stars) by Johnson et al. (2006, 2007). To the best of our knowledge, this planet – search survey is still on going. The four planets published from this survey, with metallicity of (Fe/H = 0.11, −0.15, 0.12 and −0.07, Johnson et al. 2006, 2007) are compatible with a normal metal distribution. We are eager to see the final results of this and similar surveys and to compare their metal distributions with ours.

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