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The metallicity of nearby dwarfs and giants: Implications on the planet metallicity correlation

J. Maldonado[1,2]*, E. Villaver[1] and C. Eiroa[1]

[1]*Universidad Autónoma de Madrid, Dpto. Física Teórica, Módulo 15, Facultad de Ciencias, Campus de Cantoblanco, E-28049 Madrid, Spain*

[2]*INAF Osservatorio Astronomico di Palermo, Piazza Parlamento 1, 90134 Palermo, Italy*

Abstract. Differences in the metal content of dwarfs and giant stars belonging to the same open cluster have been reported in the literature. Such differences, if confirmed, can put into question recent results pointing towards a lack of a gas-giant planet metallicity correlation in samples of giant stars with planets. In this contribution we use our large database of stellar spectra collected during the last years to test whether there are or not differences between the metallicity distribution of nearby dwarfs and giants. We use the results to discuss our latest results concerning the metallicity distribution of evolved planet hosts.

Keywords : – techniques: spectroscopic – stars: abundances – stars: late-type –stars: planetary systems

1. Introduction

Understanding the origin and evolution of stars and planets is one of the major goals of modern astrophysics. Most of our current knowledge on planet formation is still based on observations of main-sequence (MS) solar-type stars. In particular, a correlation between stellar metallicity and probability of hosting a gas-giant planet has been firmly established (Santos, Israelian & Mayor 2004; Valenti & Fischer 2005). But besides that, any other claim a of special property or trend in exoplanet hosts has been so far disputed. Even the giant-planet metallicity correlation (PMC) has revealed more complex than initially expected as stars hosting low-mass planets do not show the metal-rich signature (Ghezzi et al. 2010b; Mayor et al. 2011; Sousa et al. 2011).

*email: jesus.maldonado@uam.es, jmaldonado@astropa.inaf.it

Little is known about planet formation around massive stars (stars earlier than late-F). Their spectra dominated by broad hydrogen lines and their high levels of stellar rotation make them unsuitable targets for radial velocity searches. Studies on massive stars have focused in samples of evolved stars (subgiants and red giants) as once the star leaves off the main-sequence it spins down and becomes cooler. Such studies have succeeded in discovering a wide variety of planets, opening the possibility of testing planet formation and evolution in a different environment (e.g. Frink et al. 2002; Sato et al. 2003; Johnson et al. 2007; Niedzielski et al. 2007).

The properties of evolved planet hosts are, however, not well constrained since previous works are mainly based on small and/or inhomogeneous samples. Evidence that subgiant stars with planets might follow the PMC has been reported by Valenti & Fischer (2005); Ghezzi et al. (2010a); Johnson et al. (2010). The results for the giant hosts have been puzzling so far, while the works of Sadakane et al. (2005); Schuler et al. (2005); Pasquini et al. (2007); Takeda, Sato & Murata (2008); Ghezzi et al. (2010a) point towards a lack of a PMC in giant hosts, Hekker & Meléndez (2007) find that the PMC could also holds for giants. In a recent work, Maldonado, Villaver & Eiroa (2013) show that the metallicity distribution of planet hosting subgiant and giant stars with $M_\star > 1.5\ M_\odot$ fits well in the core-accretion scenario. However, giant planet hosts with $M_\star \leq 1.5\ M_\odot$ do not show the PMC.

Studies of dwarfs and giants in some open clusters have revealed possible differences in the metallicity of dwarfs and giants (see for a review, Pace 2011, and references therein). Whether these differences are real, an effect of inhomogeneous analysis, or indicate processes not well understood in modeling the atmospheres of evolved stars, should be addressed before a *direct* comparison of the metallicity distribution of dwarfs and giants with/without planetary companions is performed.

In this contribution we make use of our large database of stellar spectra collected during the last years to perform an homogeneous comparison of the metallicity of a large sample of nearby main-sequence and giant stars. We focus on nearby stars (instead of stars in clusters) since these are the stars that are usually included in exoplanet search programs.

2. Stellar sample, observations, and analysis

During the last years our team has collected a significant number of high-resolution, high S/N, and wide spectral coverage échelle spectra. Spectroscopic observations were carried out in several observing runs at different 2 meter-class telescopes with different facilities. In brief, the data were taken with the following spectrographs and telescopes: i) FOCES (Pfeiffer et al. 1998) at the 2.2 meter telescope of the Calar Alto observatory (Almería, Spain); ii) SARG (Gratton et al. 2001) at the TNG, La Palma (Canary Islands, Spain); iii) FIES (Frandsen & Lindberg 1999) at the NOT, La Palma; and iv) the HERMES instrument (Raskin et al. 2011) at the MERCATOR telescope,

La Palma; We also used additional spectra from the public library "S^{4}N" (Allende Prieto et al. 2004), which contains spectra taken with the 2dcoudé spectrograph at McDonald Observatory and the FEROS instrument at the ESO 1.52 m telescope in La Silla, and from the ESO/ST-ECF Science Archive Facility [1] (specifically FEROS spectra). Full details regarding the observations and data reduction can be found in Maldonado et al. (2010, 2012, 2013); Martínez-Arnáiz et al. (2010).

From these works we have selected a total of 93 nearby (d < 25 pc) late-type (Hipparcos spectral type between F5 and K2-K3) main sequence stars with homogeneous parameters determined in Maldonado et al. (2012, hereafter MA12). Stars with known planetary companions are excluded. The giant sample consists of 67 giant stars selected from the compilation of Massarotti et al. (2008) with homogeneous parameters computed in Maldonado et al. (2013, hereafter MA13). Since lists of not-planet detection are *usually* not published, we can not rule out the possibility of undetected planets around some of the stars in both samples.

The basic stellar parameters $T_{\rm eff}$, $\log g$, microturbulent velocity (ξ_t), and [Fe/H] are determined using the codes TGV (stars from MA12 paper) and its updated version TGVIT [2] (stars from MA13 paper) (Takeda et al. 2005), which implement the iron ionization and excitation equilibrium conditions. ATLAS9 plane-parallel LTE atmosphere models (Kurucz 1993) are used as inputs for TGVIT as well as the equivalent width of a set of isolated Fe I and Fe II lines. For the equivalent width measurements the automatic routine ARES [3] (Sousa et al. 2007) and the IRAF [4] task *splot* were used. TGVIT derives only "statistical" uncertainties in the sense that it progressively changes the best solution until any of the conditions iron ionization/excitation match of the curve of growth is not longer fulfilled. We are aware that other sources of uncertainty such as the choice of the atmosphere model or the adopted atomic parameters are not considered.

We note that ideally all our targets should have been observed with the same spectrograph using the same configuration. Nevertheless, all the spectra used here have a similar resolution, cover enough Fe lines, and the same methodology has been applied.

3. Results

The metallicity distribution of MS and nearby giant stars are compared in the left panel of Fig. 1. It is clear from the figure that both samples show a very similar

[1] http://archive.eso.org/cms/

[2] http://optik2.mtk.nao.ac.jp/ takeda/tgv/

[3] http://www.astro.up.pt/ sousasag/ares/

[4] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Table 1. [Fe/H] statistics of the stellar samples

Sample	*Mean*	*Median*	*Deviation*	*Min*	*Max*	*N*
Main Sequence	-0.09	-0.02	0.27	-1.12	0.36	93
Giants	-0.06	-0.03	0.18	-0.50	0.28	67

distribution. In particular, we note that they show similar statistics, mean and median values, see Table 1. We note, however, that in the sample of giants there are no metal-poor stars (stars with metallicities below -0.50 dex) which is not the case for MS, which contains stars with metallicities as low as -1.12 dex. A standard two-sample Kolmogorov-Smirnov test (K-S) [5] gives a 70% for the metallicity distribution of main sequence and giants being drawn from the same parent population (D-value $\sim$ 0.11, $n_{eff} \sim 39$).

The "deficit" of low-metallicity giants is more evident in the right panel of Fig. 1 where the cumulative distribution function of both samples are shown. Whether this deficit is real or not is difficult to say. Our reference sample of giants comes from the compilation of nearby (d < 100 pc) evolved stars of Massarotti et al. (2008). Exoplanet search programs usually apply colour cut-offs which may lead to exclusion of metal-rich giants in the samples of stars which are targeted (Mortier et al. 2013). If a similar selection effect were present in the reference sample, it could explain an excess of low-metallicity giants (with respect to metal-rich stars), but definitely not a deficit.

As in our previous works, we have compared both samples in terms of distance and stellar age, the parameters more likely to affect the metal content of a star. We do not discuss kinematics here, since as shown in MA13, and Maldonado et al. (2010) most of these stars show Galactic spatial-velocity components (U, V, W) in agreement with the thin disc population.

The sample of MS stars is drawn from a survey of nearby stars and is volume limited up to 25 pc (mean distance $\sim$ 16 pc) while the sample of giant stars covers a distance range between 19 and 107 pc (mean distance $\sim$ 75 pc). This certainly constitutes a bias that should be discussed. If the sample of giants were contaminated by stars not born in the solar neighbourhood we would expect this sample to show a large spread in metallicity values. Rather than this, we find that the metallicity distribution of giants is narrower than that of the dwarfs.

On the other hand, stellar age is one of the most difficult parameters to determine accurately. Ages for the MS stars are derived from log R'_{HK} values, following the relationship provided by Mamajek & Hillenbrand (2008). This relationship has

[5] The routine KSTWO available at The IDL Astronomy User's Library, http://idlastro.gsfc.nasa.gov/, has been used.

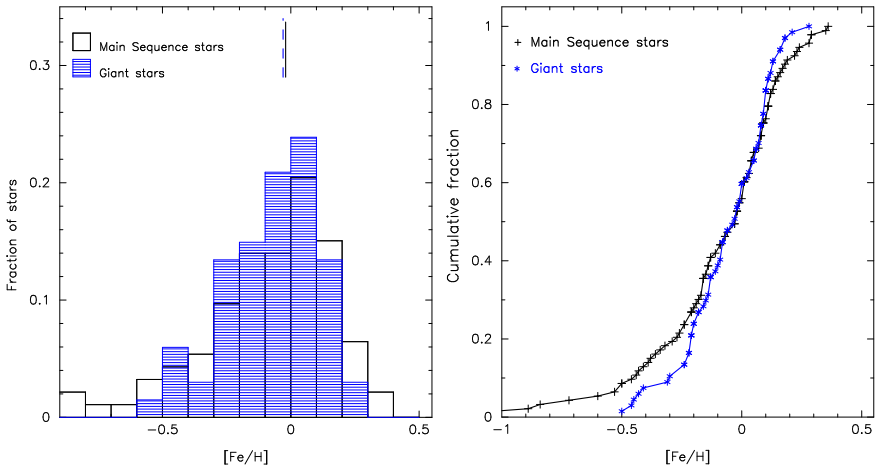

Figure 1. Left: Normalized metallicity distribution of giant stars (blue histogram shaded at 0 degrees) versus MS stars (empty histogram). Median values of the distributions are shown with vertical lines. Right: Histogram of cumulative frequencies for the sample of MS stars (black crosses) and the sample of nearby giants (blue asterisks).

an accuracy of 15-20% for young stars, i.e. younger than 0.5 Gyr, and at older age, uncertainties can grow by up to 60%. For the giant sample, ages are derived from HIPPARCOS V magnitudes and parallaxes using using L. Girardi's code PARAM[6], which is based on the use of Bayesian methods (da Silva et al. 2006). We are aware that ideally stellar ages should have been computed using the same procedure but, unfortunately, isocrhones do not work for late-type main-sequence stars whilst there are almost no estimates of log R'_{HK} values for evolved stars. The [Fe/H] vs stellar age diagram is shown in Fig. 2. It is clear from this Figure that the MS sample contains a fraction of young stars (younger than 0.2 Gyr) while this is not the case for the giant sample. Besides that, MS and giants show a similar behaviour. In particular, the young stars in the MS sample do not seem to have higher metallicities, therefore we can rule out a possible chemical evolution in the MS sample.

4. Implications on the planet metallicity-correlation

We found that when applying an homogeneous procedure nearby main sequence and giant stars show a common metallicity scale, although some differences may exist between the samples in terms of age or distance. This result has implications in our understanding of how planets and planetary systems form.

Since the metallicity scale of late-type stars does not seem to depend on the evo-

[6]http://stev.oapd.inaf.it/cgi-bin/param_1.1

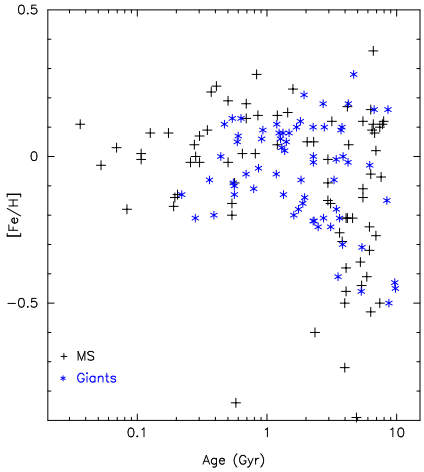

Figure 2. [Fe/H] versus age for the stars in the MS (black crosses) and in the giants (blue asterisks) samples.

lutionary stage it is therefore possible to perform a direct comparison of metal content of samples of main-sequence, subgiants and giants stars, providing a way to test whether the PMC holds for evolved stars. In MA13, we have shown that while subgiant stars with planets show the metal-rich signature, this is not the case for giant planet-hosts. Since we have not found differences in the metallicity between giants and dwarfs, our results do not affect MA13 conclusions. We also note that the deficit of low-metallicity giant stars in the MA13 sample does not contradict the lack of a PMC in giants, since even without metal-poor stars, giants with planets do not show metal-enrichment (see MA13, Fig. 9).

Two main scenarios for planet formation has been proposed to explain the PMC observed in MS stars, and their lack of it in giants. In the pollution-scenario (Gonzalez 1997) the metal-rich signature observed in planet hosts is due the accretion of gas-depleted material on the stellar surface. Only the external layers of the stellar atmosphere are affected and the metal-rich signature disappears as the star evolves and its convective zone grows. On the other hand, in the framework of core-accretion models, recent simulations of planet formation (Alibert, Mordasini & Benz 2011; Mordasini et al. 2012) have shown that high-mass protoplanetary disks can compensate low-metallicity environments allowing the formation of giant planets even around low-metallicity stars.

However, MA13 also found that a clear segregation in stellar mass appears around 1.5 $M_{\odot}$ (see MA13, Figs. 10 and 11), giant planet hosts below this mass do not tend to be preferentially metal-rich but giant stars with stellar masses $M_{\star} > 1.5$ $M_{\odot}$ do show the PMC. This mass segregation is however difficult to explain. *i)* According to the core-accretion scenario, low-metallicity can be compensated by higher mass protoplanetary disks, but the sample of low-mass giants show similar masses than

the subgiants where the PMC is found. *ii)* We did not find evidence of chemical pollution, and there is anyway no physical reason why the convection would alter the metal signature only in the giants with $M_\star \leq 1.5$ $M_\odot$. *iii)* Giants with masses larger than 1.5 $M_\odot$ are younger than the other analyzed samples ruling out Galactic radial mixing as an explanation (Haywood 2009). An option that we cannot exclude is the risk of the giant hosts sample being biased. As noticed by Mortier et al. (2013) because of the colour cut-off applied in planet search programs, metal-rich giant stars could be left out of the samples, which may prevent us from reproducing a PMC in giants.

5. Summary

In this contribution we have made an extensive use of our large database of high-resolution spectra and homogeneously derived stellar parameters to compare the metallicity distribution of a large sample of nearby main sequence and giant stars.

We find that both samples show a similar metallicity distribution, although a deficit of metal-poor ([Fe/H]) < -0.5 dex) giants is present in our sample. We therefore confirm recent results pointing towards a lack of a PMC in giant stars, ruling out the possibility that such result could be an effect of a different metallicity scale between giants and dwarfs.

We finally stress the need of using high-quality data and following an analysis as homogeneous as possible. That could be behind the differences in metallicity found between dwarfs and giants in some open clusters. A carefully analysis of the data from the ongoing Gaia-ESO survey (Gilmore et al. 2012) will certainly shed more light into this issue.

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