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Signatures of Earth-Like Planets in the Chemical Composition of Solar-Type Stars

Jorge Meléndez[1] **and Iván Ramírez**[2]

[1]Departamento de Astronomia do IAG/USP, Universidade de São Paulo, Rua do Matão 1226,
Cidade Universitária, 05508-900 São Paulo, SP, Brazil.
email: `jorge@astro.iag.usp.br`

[2]McDonald Observatory and Department of Astronomy, University of Texas at Austin,
2515 Speedway, Stop C1400, Austin, Texas 78712-1205

Abstract. The formation of terrestrial and gas giant planets has likely imprinted signatures on the chemical composition of their parent stars, as shown for example by the higher occurrence of giant planets for higher stellar metallicities. There are two new signatures that have been recently proposed by Meléndez *et al.* (2009, 2012) and Ramírez *et al.* (2009, 2010) for the formation of rocky planets, and by Ramírez *et al.* (2011) for gas giant planets. We review here our on-going work on the planet-star connection using solar twins, for which chemical abundances are being obtained at unprecedented precision (0.01 dex).

Keywords. solar system: formation, Earth, stars: abundances, planetary systems: formation

1. Introduction

The processes of star and planet formation are far from fully understood, but we know that they occur nearly at the same time. Thus, it is likely that the formation of both terrestrial and gas giant planets has imprinted signatures in the chemical composition of their host stars. During the final phases of gas accretion by the star, when the protoplanetary nebula cools, dust grain condensates and later coagulates to form planetesimals and finally terrestrial planets in the inner region, while in the outer region rocky-ice embryos will accrete hydrogen and helium to form the gas giant planets (Morbidelli *et al.* 2012), although giant planets could also form by gravitational disk instability. The chemical fingerprints left by these processes are key to constrain different models of planet formation. The classical example of the star-planet connection is the well-known planet-metallicity correlation in solar type stars, indicating that a higher abundance of metals increases the probability of forming giant planets (Gonzalez 1997). This signature has been confirmed by further works (e.g. Fischer & Valenti 2005; Udry & Santos 2007; Ghezzi *et al.* 2010) and may favor the theory of core-accretion for giant planet formation.

Although the correlation between giant planet frequency and overall stellar metallicity has been important in the context of planet formation, it is probably only the tip of the iceberg regarding the connection between stars and planets. In the subsequent decade after the seminal work by Gonzalez (1997), there have been many attempts to explore other relations between planets and the abundance of specific chemical elements, but no clear result was obtained (Udry & Santos 2007), probably due to the relatively large uncertainties (about 0.05 dex) in the determination of chemical abundances (Asplund 2005), or in same cases due to a bias in the comparison between stars with and without planets, as shown for example for lithium, for which a fare comparison found no difference in the Li abundances of the two samples (Baumann *et al.* 2010).

Errors as low as 0.01 dex could be obtained in a strict differential analysis of a sample of stars that are very similar to each other (due to the cancellation of systematic errors), opening thus new windows on the planet-star connection. Indeed, recent works on high precision chemical abundances are giving further clues on the formation of rocky (Meléndez *et al.* 2009) and giant (Ramírez *et al.* 2011) planets.

2. Signatures of terrestrial planet formation

A new era on precise chemical abundance determinations started with the analysis of 11 solar twins by Meléndez *et al.* (2009). As these stars have both stellar parameters and spectra nearly indistinguishable from the Sun, many systematic errors that plague stellar abundance analyses are canceled in a strictly line-by-line differential analysis of the solar twins relative to the Sun, being possible to achieve an unprecedented precision of 0.01 dex (Meléndez *et al.* 2009; Meléndez *et al.* 2012), about a factor of 5 smaller than standard abundance analyses. This dramatic improvement is critical to explore the small effects that planet formation may imprint on the chemical composition of stars.

Meléndez *et al.* (2009) found that the Sun is peculiar when compared to a sample of 11 solar twins (Fig. 1a). The abundance of refractory elements (those that condensed at high temperatures in the inner solar nebula) is systematically smaller in the Sun relative to the solar twins. The amount of material missing is compatible with the amount needed to form the terrestrial planets (Meléndez *et al.* 2009; Gustafsson *et al.* 2010; Chambers 2010), meaning that the deficiency of refractory elements in the solar photosphere would disappear if the rocky material formed in the solar system were diluted into the present-day solar convective envelope (Chambers 2010; Meléndez *et al.* 2012), as shown in Fig. 1b. This opens the exciting possibility of discovering stars that could potentially host terrestrial planets based on a careful chemical abundance analysis, but certainly further work is needed to consider this as a firm signature of rocky planets.

If the above signature is confirmed, then stars with chemical composition similar to solar could potentially host terrestrial planets. So far the star that has the composition most similar to the Sun is the solar twin HIP 56948 (Meléndez & Ramírez 2007; Meléndez

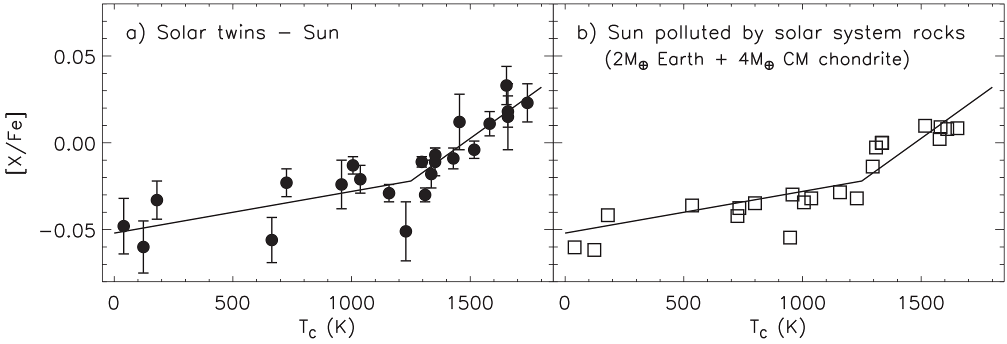

Figure 1. a) Average elemental abundance ratios (relative to Fe) as a function of condensation temperature for 11 solar twin stars from Meléndez *et al.* (2009). This clear correlation between [X/Fe] and $T_{\rm C}$ was not detected before due to the large errors in standard chemical composition analysis ($\sim \pm 0.05$ dex). In Meléndez *et al.* (2009), the [X/Fe] values have errors of about 0.01 dex. The solid line is a linear fit to the data, but broken at $T_{\rm C} = 1250$ K. **b)** Variation of the solar photospheric abundances, relative to Fe, if the Sun's present-day convective envelope were polluted by 2 Earth masses of Earth-like material and 4 Earth masses of CM chondrite rocks. Note the excellent agreement with the linear fit to the solar twin chemical abundance data (the solid line in this panel is the same as in panel a). Adapted from Meléndez *et al.* (2012).

et al. 2012). This star has also other properties (mass, temperature, luminosity) essentially identical to solar. Interestingly, the precise radial velocity observations obtained for this star at the McDonald and Keck observatories show no signs of giant planets within and in the habitable zone, making this star an excellent candidate for hosting habitable rocky planets.

3. Is there any other explanation for the Sun's abundance anomalies?

As discussed extensively in Meléndez *et al.* (2009, 2012), the abundances anomalies cannot be explained by other causes such as contamination from AGB stars, SNIa, SNII or HN (Fig. 2), or by Galactic chemical evolution processes or age effects. Kiselman *et al.* (2011) have shown that the peculiar abundance pattern cannot be attributed to line-of-sight inclination effects. Also, the abundance trend does not arise due to the particular reflection properties of asteroids. Although the abundance peculiarities may indicate that the Sun was born in a massive open cluster like M67 (Önehag *et al.* 2011), this explanation is based on the analysis of only one solar twin.

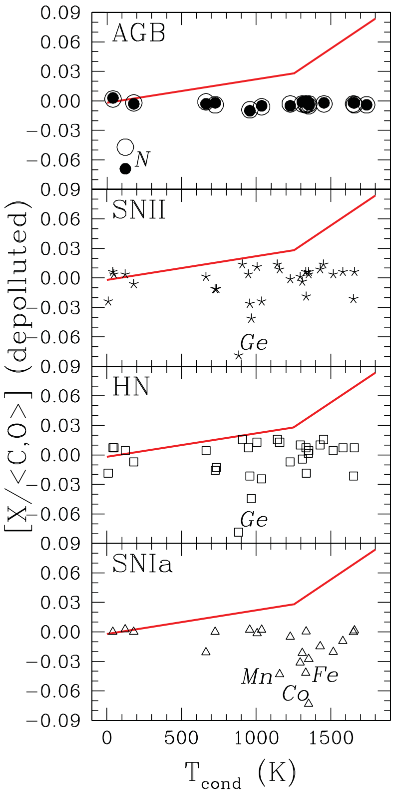

Figure 2. Abundance ratios obtained after de-polluting the solar nebula from contamination by an AGB star (circles), SNII (stars), hypernova (squares) and SNIa (triangles). In the top panel the effect of adopting different solar abundances (open circles: Anders & Grevesse 1989; filled circles: Asplund *et al.* 2009) is shown. The solid line represents the mean abundance pattern of 11 solar twins relative to the Sun (Meléndez *et al.* 2009). None of the pollution scenarios can explain the trend with condensation temperature. The chemical elements that change the most are labeled. Figure taken from Meléndez *et al.* (2012).

So far the best explanation for the abundance trend seems to be the formation of terrestrial planets. The Kepler mission should detect the first Earth-sized planets in the habitable zones of solar type stars. We look forward to using 8-10 m telescopes to perform careful differential abundance analyses of those stars, in order to verify if our chemical signatures indeed imply rocky planets.

4. New signatures of giant planet formation

Regarding the formation of giant planets, we have recently studied the pair of solar analogs 16 Cyg A and B. This pair is very important to understand more about giant planet formation, because the star 16 Cyg B hosts a gas giant planet at 1.7 A.U. (Cochran *et al.* 1997), while no planets have been detected yet around 16 Cyg A. The binary pair is supposed to have the same chemical composition, as it was formed from the same natal cloud, unless the formation of the giant planet around 16 Cyg B altered its chemical abundances.

Our careful differential abundance analysis between 16 Cyg A and B showed that the component B is systematically more metal-poor, by about 10% (~0.04 dex), in the two dozen chemical elements analyzed (Ramírez *et al.* 2011), as shown in Fig. 3. Thus, it seems that the formation of the gas giant around 16 Cyg B robbed a fraction of the metals present in its parent nebula (Ramírez *et al.* 2011). Nevertheless, another abundance analysis (at somewhat lower precision) published nearly at the same date,

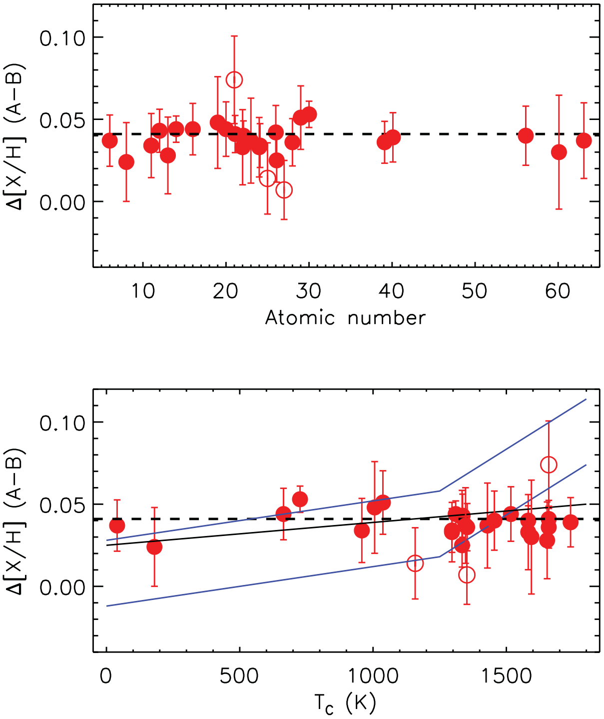

Figure 3. Top panel: elemental abundance difference between 16 Cyg A and B as a function of atomic number. Open symbols show the three species more discrepant from the mean: Sc I (21), Mn (25), and Co (27). Bottom panel: as in the top panel for the abundance differences versus dust condensation temperature. The dashed line is at +0.041 while the solid lines represent the mean trend of solar twins by Meléndez *et al.* (2009) with two arbitrary offsets. The dot-dashed line corresponds to a slope of 1.4×10^{-5} dex K^{-1}, as derived by Laws & Gonzalez (2001).

showed no difference between the abundance pattern of components A and B (Schuler *et al.* 2011). Although the spectra used by Ramírez *et al.* (2011) have a higher resolving power and a higher precision was achieved, it would be important to perform a new abundance analysis of the pair to confirm the signature of giant planet formation.

5. Planet search around solar twins

The above signatures of terrestrial and giant planets are telling us that there could be a close connection between stellar chemical composition and planet architecture. Solar twins are ideal to obtain very precise stellar abundances but unfortunately planet information is lacking for most of them, so currently we cannot study in detail the relation between chemical abundance anomalies and different type of planets.

The synergy between the high precision (0.01 dex) chemical abundances obtained in solar twins (Fig. 4) and high precision (1m s^{-1}) radial velocities that can be obtained with HARPS, can give us new insights into the planet-stellar connection. In order to study with unprecedented detail the connection between chemical abundances and planet architecture, we have been granted 88 nights with HARPS for a Large ESO Programme that started in October 2011 and should continue until 2015. This in an international collaboration involving astronomers from Brazil, Germany, USA and Australia.

Around 70 solar twins are being observed at the ESO La Silla observatory and already some of them are showing radial velocity variations compatible with Saturn and Jupiter-mass planets. For all the sample stars we have acquired high resolution high S/N spectra using the MIKE spectrograph at the 6.5 m Magellan telescope in Las Campanas, in order to obtain a homogeneous set of high precision (0.01 dex) chemical abundances. Also, some stars have spectra of even better quality acquired with UVES at the VLT.

Our initial chemical abundance analyses show that on a star-by-star basis we can obtain chemical abundances with a precision at the 0.004 - 0.008 dex level, i.e., even better than initially anticipated (0.01 dex). For the solar twin HIP 56948, the element-to-element scatter is only 0.004 dex for the volatile elements and 0.008 dex for the refractories

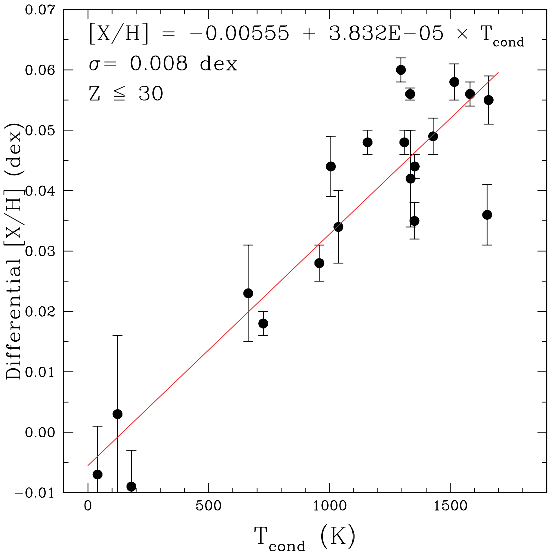

Figure 4. Trend with dust condensation temperature for the solar twin 18 Sco (Meléndez *et al.*, in preparation). The element-to-element scatter is only 0.008 dex.

(Meléndez *et al.* 2012), and our on-going work on the solar twin 18 Sco shows also an element-to-element scatter of only 0.008 dex (Fig 4). Similar results are being obtained for other solar twins.

6. Conclusions

Our work has shown that it is possible to obtain chemical abundances with a precision of about 0.01 dex or even better (∼0.005 dex) in some cases (Meléndez *et al.* 2012). This unprecedented precision was necessary to unravel the possible connection between abundance anomalies in the Sun and the formation of terrestrial planets (Meléndez *et al.* 2009; Ramírez *et al.* 2009), and to suggest a new abundance signature of giant planet formation (Ramírez *et al.* 2011). Our on-going planet search around solar twins will allow us to study at unparalleled precision any connection that may exist between planet architecture and chemical abundance peculiarities.

References

Anders, E. & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
Asplund, M. 2005, *ARAA*, 43, 481
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARAA*, 47, 481
Baumann, P., Ramírez, I., Meléndez, J., Asplund, M., & Lind, K. 2010, *A&A*, 519, A87
Chambers, J. E. 2010, *ApJ*, 724, 92
Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G. W. 1997, *ApJ*, 483, 457
Fischer, D. A. & Valenti, J. 2005, *ApJ*, 622, 1102
Ghezzi, L., Cunha, K., Smith, V. V., *et al.* 2010, *ApJ*, 720, 1290
Gonzalez, G. 1997, *MNRAS*, 285, 403
Gustafsson, B., Meléndez, J., Asplund, M., & Yong, D. 2010, *Ap&SS*, 328, 185
Kiselman, D., Pereira, T. M. D., Gustafsson, B., *et al.* 2011, *A&A*, 535, A14
Laws, C. & Gonzalez, G. 2001, *ApJ*, 553, 405
Meléndez, J. & Ramírez, I. 2007, *ApJ* (Letters), 669, L89
Meléndez, J., Asplund, M., Gustafsson, B., & Yong, D. 2009, *ApJ* (Letters), 704, L66
Meléndez, J., Bergemann, M., Cohen, J. G., *et al.* 2012, *A&A*, 543, A29
Morbidelli, A., Lunine, J. I., O'Brien, D. P., Raymond, S. N., & Walsh, K. J. 2012, *Ann. Rev. Earth Planet. Sci.*, 40, 251
Önehag, A., Korn, A., Gustafsson, B., Stempels, E., & Vandenberg, D. A. 2011, *A&A*, 528, A85
Ramírez, I., Meléndez, J., & Asplund, M. 2009, *A&A*, 508, L17
Ramírez, I., Asplund, M., Baumann, P., Meléndez, J., & Bensby, T. 2010, *A&A*, 521, A33
Ramírez, I., Meléndez, J., Cornejo, D., Roederer, I. U., & Fish, J. R. 2011, *ApJ*, 740, 76
Schuler, S. C., Cunha, K., Smith, V. V., *et al.* 2011, *ApJ* (Letters), 737, L32
Udry, S. & Santos, N. C. 2007, *ARAA*, 45, 397