Formation and evolution of exoplanets in different environments

Vardan Adibekyan¹

¹Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal; vadibekyan@astro.up.pt

Abstract.

The ultimate goal of exoplanetologists is to discover life outside our Earth and to fully understand our place in the Universe. Even though we have never been closer to attaining this goal, we still need to understand how and where the planets (efficiently) form. In this manuscript I briefly discuss the important role of stellar metallicity and chemistry on the formation and evolution of exoplanets.

1. Introduction

Ever since the first giant exoplanet was discovered orbiting a Sun-like star about twenty years ago (Mayor & Queloz 1995), the search has been ongoing for small, rocky planets around other stars, evocative of Earth and other terrestrial planets in the Solar System. As of today, there are more than 3500 planets detected¹ and several thousand candidates (Coughlin et al. 2016) waiting for validation. These discoveries helped us to understand that extra-solar planets are very common in our Galaxy. The diversity of the discovered planets is astonishing, and most of detected planets brought us more questions than answers. While the Universe is full of surprises, we (exoplanetologists) are drawing closer to the answer to the most daring questions of humankind: are we alone in the Universe and what is our place in there? In fact, the last “simplistic” calculations² of Behroozi & Peeples (2015) shows that the chance that we are the only civilization the Universe will ever have is less than 8%.

In this manuscript first I start by briefly presenting how different are the properties of so-far detected exoplanets and how the two completely (ideologically) different theories are getting close to explain the formation and evolution of these planets. In the second part of the paper I discuss the importance of chemical conditions of the environment where the exoplanets form.

2. The zoo of exoplanets and their formation scenarios

Among the few thousands of the detected exoplanets, we observed many words that are very different from what we have in our Solar System and from what we could imagine. We observed a planet with an extremely eccentric orbit of 0.97 (HD20782b – O’Toole

¹exoplanet.eu

²The authors did not consider requirements of individual elemental abundances for planet formation (e.g. Adibekyan et al. 2012b, 2015).
et al. 2009), a planet in a circumbinary orbit surrounded by four suns (PH1b³/Kepler-64b – Schwamb et al. 2013), a dense “superplanet”⁴ with a radius of only \( \sim 1 R_\oplus \) and mass of \( \sim 22 M_\oplus \) (CoRoT-3b – Deleuil et al. 2008), a very hot planet with a surface day-side temperature of more than 9000 K orbiting its pulsating hot sun in less than six hours (Kepler-70b/KOI-55.01 – Charpinet et al. 2011). The detection of these weird exoplanets⁵ puts to shame many old science fiction stories and make harder the job of new science fiction writers.

![Figure 1](image.png)

**Figure 1.** *Left:* The distribution of discovered planets in the period–mass diagram. *Right:* Mass of the known planets as a function of the discovery year. Different symbols represents planets discovered by different detection techniques. Some of the planets of our Solar System are shown for reference.

The distribution of exoplanets in the period – mass diagram is shown in Fig. 1. First, the plot shows that different planet detection techniques occupy different regions of this diagram. Second, one can see that the detected planets, while being very diverse in their properties (see previous paragraph), are clustered in three main groups: hot-Jupiters \( (M_p \sim 1-2 M_\oplus \) and \( P \lesssim 10 \) days), hot/warm super-Earths/Neptunes \( (M_p \sim 10 M_\oplus \) and \( P \lesssim 100 \) days), and gas and ice giants \( (M_p \sim 1-2 M_\oplus \) and \( P \sim 1000 \) days). We note that this diagram is strongly constrained by the biases and detection limits of different techniques. In particular the detection limits of these techniques and current instrumentation is responsible for the empty bottom-right triangle of the figure. However, some of the observed features, such as the “period-valley” (a lack of giant planets with periods between 10-100 days: Udry et al. 2003) or the sub-Jovian desert (a lack of sub-Jupiter mass planets at orbital periods shorter than 3 days: Szabó & Kiss 2011) are probably physical and give important insights for our understanding of exoplanet formation and evolution. For a recent excellent review on the architecture of exoplanetary systems we refer the reader to Winn & Fabrycky (2015).

A logical question now to ask is how do these very different planets form? Currently two main mechanisms are proposed for the formation of exoplanet that are con-

---

³This planet was first discovered by two citizen scientists.

⁴Note that this sub-stellar object can be a low-mass brown-dwarf.

⁵[https://en.wikipedia.org/wiki/List_of_exoplanet_extremes](https://en.wikipedia.org/wiki/List_of_exoplanet_extremes)
ceptually different. In the so called core-accretion (CA) model low-mass planets form from the coagulation of very small solid bodies (Pollack et al. 1996). If before the dissipation of the protoplanetary disk, a core of about 5-10 M⊕ is formed then, it can undergo runaway accretion of gas and form a giant planet. In the so called gravitational instability (GI), in the gaseous disk (usually massive and cold), localized instabilities collapse into giant planets (Boss 1998). These two models have experienced substantial development and modifications, and the most recent and advanced ones (e.g. Nayakshin 2016; Bitsch et al. 2015; Levison et al. 2015) include important phenomena such as pebble accretion (e.g. Johansen & Lacerda 2010) and/or migration in the disk (e.g. Alibert et al. 2004). Planetary population synthesis calculations (Ida & Lin 2004) based both on CA (e.g. Mordasini et al. 2009; Hasegawa & Pudritz 2013) and GI followed by tidal downsizing (TD – e.g. Forgan & Rice 2013; Nayakshin 2016) reproduce many of the properties of the observed exoplanets. We refer the reader to Mordasini et al. (2015) for a recent review on the Global models of planet formation and evolution.

3. Exoplanets and stellar metallicity

The correlation between stellar metallicity and the occurrence rate of giant planets is a firmly established fact (e.g. Gonzalez 1997; Santos et al. 2001), however, the exact functional form of this dependence is not fully established yet (see left panel of Fig. 2; Mortier et al. 2013). This observational result got its theoretical support first in CA (e.g. Mordasini et al. 2009) and then in the TD (Nayakshin 2016). Despite the large amount of observational data, it is still not clear if the planet-metallicity correlation holds for low-mass/small-sized planets (see right panel of Fig. 2; Sousa et al. 2011; Mayor et al. 2011; Wang & Fischer 2015; Buchhave & Latham 2015; Zhu et al. 2016). This is probably because it is hard to detect these light planets (especially at large distances) and it is very difficult to create a comparison sample of stars without low-mass planets.

Figure 2. Left - Mortier et al. (2013): Frequency of giant planets as a function of metallicity and mass of the HARPS + CORALIE sample. Different functional forms are shown in different colors. Right - Mayor et al. (2011): The metallicity ([Fe/H]) distribution of stars hosting giant gaseous planets (black), planets less massive than 30 M⊕ (red), and for the global combined sample stars (blue). The latter histogram has been divided by 10 for the sake of visual comparison.

Note that most of the GI based models do not predict a strong correlation between giant planet frequency and metallicity (e.g. Boss 1998).
The importance of metallicity is not only limited to the formation efficiency of planets. Metallicity also determines the maximal mass of the exo-Neptunes (Courcol et al. 2016), the presence or absence of gaseous atmosphere of small-sized planets (Dawson et al. 2015), and the mass of the core (heavy elements) of giant planets (e.g. Miller & Fortney 2011).

![Figure 3](image_url)

Figure 3. The orbital semi-major axis of low-mass and small-size planets orbiting FGK dwarf stars. Planets detected by the RV and Transit techniques are shown with filled circles and empty star-symbols, respectively. Blue color corresponds to planets orbiting metal-rich stars ([Fe/H] ≥ -0.1) and red color corresponds to planets around metal-poor stars ([Fe/H] < -0.1). The habitable zone (Kopparapu et al. 2013) for stars of different masses is highlighted by blue shade.

It is also interesting to note that the final orbital separation of planets shows a dependence on metallicity of the system (Adibekyan et al. 2013b; Beaugé & Nesvorný 2013; Mulders et al. 2016; Adibekyan et al. 2016). Adibekyan et al. (2016), based on the previous results that low-mass and small-sized planets orbiting around metal-rich stars do not have long orbits (Adibekyan et al. 2013b), suggested that planets in the “habitable zone” should be preferentially less metallic than our Sun. Fig. 3 shows the orbital distance of low-mass (detected with RV) and small-radius (detected by transit method) planets against the mass of their host stars. The plot is based on the data of Adibekyan et al. (2016) and illustrates their findings. Here we should note that (Mulders et al. 2016) observed several Kepler planet candidates orbiting their metal-rich stars at long periods\(^7\). However, they also observed that the planet occurrence rate is two times higher for metal-poor systems when compared to the systems with super-solar metallicities.

4. Exoplanets and stellar chemistry

In stellar astrophysics, the iron content is usually used as a proxy for overall metallicity and most of the aforementioned studies followed this trend. Several works, however,

\(^7\)Note that the sample of (Mulders et al. 2016) consists of Kepler planet candidates and not only confirmed planets.
Exoplanets and metallicity

searched for chemical peculiarities of planet hosting stars in terms of abundances of individual elements. While many contradictory results can be found in the literature (e.g. Bodaghee et al. 2003; Robinson et al. 2006; Brugamyer et al. 2011; Suárez-Andrés et al. 2016a,b), the enhancement of $\alpha$-elements of iron-poor planet hosts was shown to be robust (Haywood 2008; Kang et al. 2011; Adibekyan et al. 2012a,b). Interestingly, Adibekyan et al. (2012a) showed that even low-mass/small-radius planets show $\alpha$-enhancement at low-iron regime. The right panel of Fig. 4 depicts the $\alpha$-enhancement (here Si abundance is used as a proxy for $\alpha$-elements) of iron-poor planet hosts for the HARPS sample of Adibekyan et al. (2012c). The enhancement in $\alpha$-elements relative to iron is typical for the thick disk stars (e.g. Fuhrmann 1998; Adibekyan et al. 2013a). In fact, the HARPS data suggests that the planet formation frequency is about 5.5 times higher in the thick disk (12.3±4.1%) when compared to the Galactic thin disk (2.2±1.3%) in the metallicity range of $-0.7 < [\text{Fe}/\text{H}] < -0.3$ dex.

Gonzalez (2009) recommended to use a so-called refractory index “Ref”, which quantifies the mass abundances of refractory elements (Mg, Si and Fe) important for planet formation, rather than $[\text{Fe}/\text{H}]$. The importance of this index increases in the Fe-poor region (Adibekyan et al. 2012c; Gonzalez 2014b) when one compares statistics of planets around the thin disk and thick disk stars.

Figure 4. $[\text{Si}/\text{Fe}]$ versus $[\text{Mg}/\text{Si}]$ and $[\text{Si}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ for stars with and without (gray dots) planets. The red squares refer to the Jovian hosts and the blue circles refer to the stars hosting exclusively Neptunians and super-Earths ($M < 30 \, \text{M}_\oplus$). Three stars that are hosting low-mass/small-radius planets with precise radius and mass determinations are presented with a symbol of star (Santos et al. 2015). The position of the Sun is marked with the modern sun symbol.

The studies of individual heavy elements and specific elemental ratios in stars with planets are very important because they are expected to control the structure and composition of terrestrial planets (e.g. Grasset et al. 2009; Bond et al. 2010; Thiabaud et al. 2014; Dorn et al. 2015). In particular, $\text{Mg}/\text{Si}$ and $\text{Fe}/\text{Si}$ ratios are important to constrain the internal structure of terrestrial planets (Dorn et al. 2015). Recently, Santos et al. (2015) tested these models on three terrestrial planets (see Fig. 4) and showed that
the iron mass fraction inferred from the mass-radius relationship is in good agreement with the iron abundance derived from the host star’s photospheric composition.

5. Exoplanets and Galactic chemical evolution

As discussed in the previous sections exoplanet formation efficiency, the type of the planets formed and their orbital characteristics depend on metallicity and chemical conditions. Putting all these results together one can reach to an interesting conclusion (or perhaps a speculation): i) Planets orbiting their stars in the circumstellar habitable zone have sub-solar metallicities (Fig. 3). ii) These iron-poor stars are usually enhanced in $\alpha$-elements (i.e. high Si/Fe ratio) and at the same time have high Mg/Si ratio (Fig. 4). iii) High [Mg/Si] and low [Fe/Si] abundance ratio should produce a planet of a composition and structure that is different than ours (Dorn et al. 2015). Metallicity and abundance of different elements important for planet formation varies with time and location in our Galaxy and in Universe in general. Several studies during the last decade tried to predict prevalence of terrestrial planets in our Galaxy and in the so called “Galactic habitable zone” (e.g. Lineweaver et al. 2004; Gowanlock et al. 2011; Gonzalez 2014a; Gobat & Hong 2016). Some other studies extended these works to the observable Universe (e.g. Behroozi & Peeples 2015; Zackrisson et al. 2016). We refer the reader to these interesting works for more information and details about the recent interpretations of evolution of life across space and time.

6. Conclusion

Formation efficiency, composition, structure, and even “habitability” of planets depend on the chemical conditions of the environment they form i.e. time and place in the Galaxy.

Acknowledgments. I thank the science organizing committee of Non-Stable Universe: Energetic Resources, Activity Phenomena and Evolutionary Processes for the invitation to participate to this interesting conference. I acknowledge the support from Fundação para a Ciência e Tecnologia (FCT) through national funds and from FEDER through COMPETE2020 by the following grants UID/FIS/04434/2013 & POCI-01-0145-FEDER-007672, PTDC/FIS-AST/7073/2014 & POCI-01-0145-FEDER-016880 and PTDC/FIS-AST/1526/2014 & POCI-01-0145-FEDER-016886. I also acknowledges the support from FCT through Investigador FCT contracts of reference IF/00650/2015. Finally, I would like to thank Pedro Figueira for his interesting comments and discussion.

References

Adibekyan, V., Figueira, P., & Santos, N. C. 2016, Origins of Life and Evolution of the Biosphere, 46, 351. 1509.02429
Adibekyan, V., Santos, N. C., Figueira, P., Dorn, C., Sousa, S. G., Delgado-Mena, E., Israeli, G., Hakobyan, A. A., & Mordasini, C. 2015, A&A, 581, L2. 1508.04970

*The region within the Galaxy where planets can form around stars and retain liquid water on their surface for a significant amount of time.*
Exoplanets and metallicity

Adibekyan, V. Z., Delgado Mena, E., Sousa, S. G., Santos, N. C., Israeliian, G., González Hernández, J. I., Mayor, M., & Hakobyan, A. A. 2012a, A&A, 547, A36. 1209. 6272

Adibekyan, V. Z., Figueira, P., Santos, N. C., Hakobyan, A. A., Sousa, S. G., Pace, G., Delgado Mena, E., Robin, A. C., Israeliian, G., & González Hernández, J. I. 2013a, A&A, 554, A44. 1304. 2561

Adibekyan, V. Z., Figueira, P., Santos, N. C., Mortier, A., Mordasini, C., Delgado Mena, E., Sousa, S. G., Correia, A. C. M., Israeliian, G., & Oshagh, M. 2013b, A&A, 560, A51. 1311. 2417

Adibekyan, V. Z., Santos, N. C., Sousa, S. G., Israeliian, G., Delgado Mena, E., González Hernández, J. I., Mayor, M., Lovis, C., & Udry, S. 2012b, A&A, 543, A89. 1205. 6670

Adibekyan, V. Z., Santos, N. C., Sousa, S. G., Israeliian, G., Delgado Mena, E., González Hernández, J. I., Mayor, M., & Khachatryan, G. 2012c, A&A, 545, A32. 1207. 2388

Alibert, Y., Mordasini, C., & Benz, W. 2004, A&A, 417, L25. astro-ph/0403574

Beaugé, C., & Nesvorný, D. 2013, ApJ, 763, 12. 1211. 4533

Behroozi, P., & Peeples, M. S. 2015, MNRAS, 454, 1811. 1508. 01202

Bitsch, B., Lambrechts, M., & Johansen, A. 2015, A&A, 582, A112. 1507. 05209

Bodaghee, A., Santos, N. C., Israeliian, G., & Mayor, M. 2003, A&A, 404, 715. astro-ph/0304360

Bond, J. C., O’Brien, D. P., & Lauretta, D. S. 2010, Astrophys J, 715, 1050. 1004. 0971

Boss, A. P. 1998, ApJ, 503, 923

Brugamyer, E., Dodson-Robinson, S. E., Cochran, W. D., & Sneden, C. 2011, ApJ, 738, 97. 1106. 5599

Buchhave, L. A., & Latham, D. W. 2015, ApJ, 808, 187. 1507. 03557

Charpinet, S., Fontaine, G., Brassard, P., Green, E. M., Van Grootel, V., Randall, S. K., Silvotti, R., Baran, A. S., Östensen, R. H., Kawaler, S. D., & Telting, J. H. 2011, Nat, 480, 496

Coughlin, J. L., Mullally, F., Thompson, S. E., Rowe, J. F., Burke, C. J., Latham, D. W., Batalha, N. M., Ofir, A., Quarles, B. L., Henze, C. E., Wolfgang, A., Caldwell, D. A., Bryson, S. T., Shporer, A., Catanzarite, J., Akeson, R., Barclay, T., Borucki, W. J., Boyajian, T. S., Campbell, J. R., Christiansen, J. L., Girouard, F. R., Haas, M. R., Howell, S. B., Huber, D., Jenkins, J. M., Li, J., Patil-Sabale, A., Quintana, E. V., Ramirez, S., Seader, S., Smith, J. C., Tenenbaum, P., Twicken, J. D., & Zamudio, K. A. 2016, ApJS, 224, 12. 1512. 06149

Courcol, B., Bouchy, F., & Deleuil, M. 2016, MNRAS, 461, 1841. 1604. 08560

Dawson, R. I., Chiang, E., & Lee, E. J. 2015, MNRAS, 453, 1471. 1506. 06867

Deleuil, M., Deeg, H. J., Alonso, R., Bouchy, F., Rouan, D., Auvergne, M., Baglin, A., Aigrain, S., Almenara, J. M., Barbieri, M., Barge, P., Bruntt, H., Bordé, P., Collier Cameron, A., Csizmadia, S., de La Reza, R., Dvorak, R., Erikson, A., Fridlund, M., Gandolfi, D., Gillon, M., Guenther, E., Guillot, T., Hatzes, A., Hébrard, G., Jorda, L., Lammer, H., Léger, A., Llebaria, A., Loeillet, B., Mayor, M., Mazeh, T., Moutou, C., Ollivier, M., Pázmold, M., Pont, F., Queloz, D., Rauer, H., Schneider, J., Shporer, A., Wuchterl, G., & Zucker, S. 2008, A&A, 491, 889. 0810. 0919

Dorn, C., Khan, A., Heng, K., Connolly, J. A. D., Alibert, Y., Benz, W., & Tackley, P. 2015, A&A, 577, A83. 1502. 03665

Forgan, D., & Rice, K. 2013, MNRAS, 432, 3168. 1304. 4978

Fuhrmann, K. 1998, A&A, 338, 161

Gobat, R., & Hong, S. E. 2016, A&A, 592, A96. 1605. 06627

Gonzalez, G. 1997, MNRAS, 285, 403

— 2009, MNRAS, 399, L103

— 2014a, ArXiv e-prints. 1403. 6761

— 2014b, MNRAS, 443, 393. 1406. 0861

Govanlock, M. G., Patton, D. R., & McConnell, S. M. 2011, Astrobiology, 11, 855. 1107. 1286

Grasset, O., Schneider, J., & Sotin, C. 2009, Astrophys J, 693, 722. 0902. 1640

Hasegawa, Y., & Pudritz, R. E. 2013, ApJ, 778, 78. 1310. 2009

Haywood, M. 2008, A&A, 482, 673. 0804. 2954

Ida, S., & Lin, D. N. C. 2004, ApJ, 604, 388. astro-ph/0312144
