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Reinforcement of the link between stellar metallicity and the zero age orbit of gas giant planet

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Abstract. In 2005 we suggested a relation between the optimal locus of gas giant planet formation, prior to migration, and the metallicity of the host star, based on the core accretion model, and radial profiles of dust surface density and gas temperature. At that time, less than 200 extrasolar planets were known, limiting the scope of our analysis. Here, we take into account the expanded statistics allowed by new discoveries, in order to check the validity of some premises. We compare predictions with the present available data and results for different stellar mass ranges. We find that the zero age planetary orbit (ZAPO) hypothesis continues to hold after a two order of magnitude increase in discovered planets, as well as the prediction that planets around metal poor stars would have shorter orbits.

Keywords. planetary systems, gaseous planets, formation - planets and satellites

1. Introduction

Twelve years ago, less than two hundred extrasolar planets were known, and the most successful technique employed was the radial velocity, which was used for the discovery of the first one, 51 Peg (Mayor & Queloz 1995). After that, the transit method became increasingly more productive, and, when used by the Kepler Mission (Morton *et al.* 2016, D'Angelo, Durisen e Lissauer, 2010), surpassed the radial velocity method and helped to unveil thousands of candidate planets, pushing the statistics to the present level of more than 3600 confirmed planets (Schneider *et al.* 2011).

In 2005 we proposed a relation between the optimal locus of gas giant planet formation, prior to migration, and the metallicity of the host star, which can be considered as a proxy of the metallicity of the protoplanetary disc (Pinotti *et al.* 2005). In order to build the model, we assumed a number of premises, the most fundamental of which being that the planet formation mechanism is the core accretion (D'Angelo, Durisen & Lissauer 2010, Pollack *et al.* 1996), which requires that dust evolves to planetesimals, which in turn form a rocky nucleus a few times the Earths mass, which will then capture an appreciable amount of gas from the protoplanetary disc until its final mass reaches approximately 10^2 to 10^3 Earth mass. Radial profiles of disc temperature and dust surface density were obtained from the literature; considering also that the dust surface density profile is altered by change in the discs metallicity, we developed a quantitative relation, which dictates that the optimum region of planet formation shifts outward for higher metallicity, reaching asymptotic values for both high and low values of metallicity Z. This behavior seemed to explain why, with the statistics available at the time, metal poor stars tended to harbor planets with smaller orbital radius when compared with metal rich ones. When used in a plot of stellar metallicity versus planet semi-major axis, the relation forms an S shaped curve, which we called Zero Age Planetary Orbit (ZAPO).

The dearth of gas giant planets around metal poor stars is a well-known observational fact (Mortier *et al.* 2012, Schlaufman and Laughlin 2011, Sozzetti *et al.* 2009, Fisher & Valenti 2005, Gonzalez 1997) and a natural consequence of the core accretion mechanism, since the resulting lower dust surface density would affect the formation of the rocky core (Pollack *et al.* 1996), and because a low metallicity protoplanetary disc has possibly a shorter lifetime, affecting the probability of the formation of a fully mature gas giant planet (Yasui *et al.* 2010, Ercolano & Clarke 2010). Our hypothesis would add a new cause to the observed scarcity of planets around metal poor stars, that is, the smaller formation radius would increase the fraction of planets engulfed by their stars during the migration process. In this work, we used the new available statistics to assess the validity of some of our premises, check if the predictions are still valid, and compare results for different stellar mass ranges.

2. Development of the hypothesis

For more details about the development see Pinotti, Boechat-Roberty and Porto de Mello (2017) and Pinotti *et al.* (2005). Briefly, the probability P of gas giant planet formation as a function of the radius r is proportional to the dust surface density σ_s and the disk mid-plane temperature T,

$$P \propto \sigma_s/T \tag{2.1}$$

The radial profiles of σ_s and T are in the form of power laws:
$\sigma_s \propto \mathrm{r}^{-\alpha}$
$\mathrm{T} \propto \mathrm{r}^{-\beta} + \mathrm{t}$
$\alpha = \alpha(\mathrm{Z})$ and $\beta = \beta(\mathrm{Z})$, where Z is the metallicity of the disk.
The optimum formation radius $\mathrm{r}_{opt}(Z)$ is given by

$$r_{opt}(Z) = \left(\frac{(\beta_a - \alpha_a)}{t\alpha_a}\right)^{\frac{1}{\beta(Z)}} \tag{2.2}$$

where t, α_a and β_a are parameters for the calibration of the ZAPO curve.

The curve exhibits two asymptotic values, for very low and very high metallicity; for the population of migrated planets we assumed $r(Z,n)= nr_{opt}(Z)$, where $\mathrm{n} < 1$. We used in our recent analysis the Extrasolar Planets Encyclopedia (Schneider *et al.* 2011) listed 3406 planets as of May 12^{th}, 2016, a number that increases steadily as new discoveries are made in a weekly basis. The criteria for the selection of planets were: data on mass, semi-major axis SMA and eccentricity, maximum and minimum mass, maximum eccentricity, maximum SMA, most massive planet in the case of multiple systems and stars with data on metallicity.

3. Results

In 2005 we used 72 planets to calibrate the ZAPO curve (Fig.1), all of them around stars with 1 ± 0.2 M_{Sun}. In 2016 the available number of adequate planets around stars with the same mass range jumped to 282 (Fig.2). All of them, except two, are at or below the ZAPO curve, as predicted. The two exceptions are planets with eccentricities close to our upper limit of 0.4, indicating planet-planet interaction. Our prediction that

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Table 1. Details of the sample of selected planets.

Stellar Mass range $M_\odot$	Average stellar mass $[M_\odot]$	Number of planets
< 0.8	0.65	38
$0.8 \leqslant M_\odot \leqslant 1.2$	1.02	282
$1.2 \leqslant M_\odot \leqslant 1.6$	1.36	138
< 1.6	1.91	46

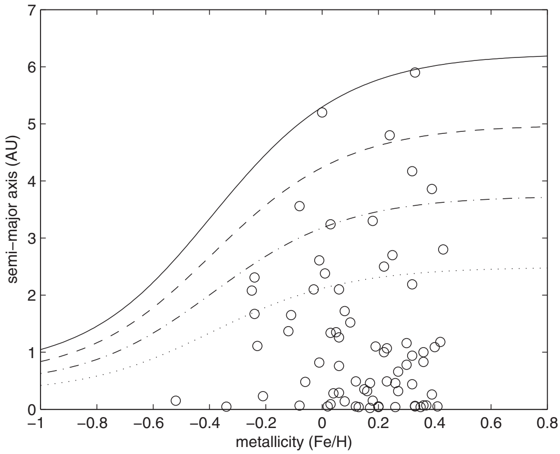

Figure 1. Semi-major axis as a function of metallicity (Fe/H). Reproduction of figure from Pinotti *et al.* 2005, showing the 72 planets used at the time, and ZAPO curve (n=1, full line), and curves for migrated planets: n=0.8 (dashed line), n=0.6 (dash-dot line) and n=0.4 (dotted line).

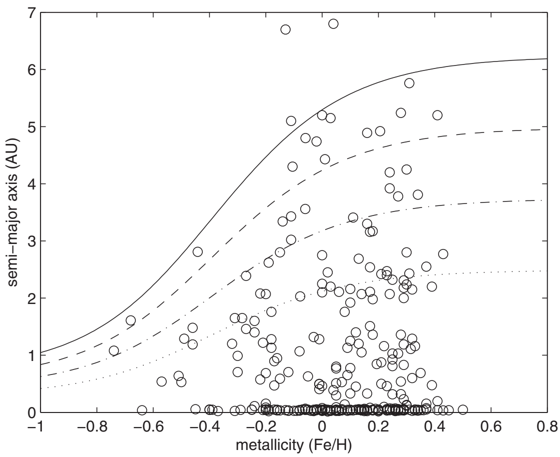

Figure 2. The same ZAPO curves of Figure 1, with the current group of 282 known planets around stars with mass range of $0.8 \leqslant M_{Sun} \leqslant 1.2$ (Pinotti *et al.* 2017).

planets around low metallicity stars will have small semi-major axes is also confirmed The ZAPO curve holds also for other stellar mass ranges.

References

D'Angelo, G., Durisen, R. H., & Lissauer, J. J., 2010, in S. Seager, ed., Exoplanets, University of Arizona Press, Tucson, p. 319

https://doi.org/10.1017/S1743921317007773 Published online by Cambridge University Press

Ercolano, B. & Clarke, C. J. 2010 *MNRAS*, 402, 2735
Fisher, D. A. & Valenti, J. 2005, *ApJ* 622, 1102
Gonzalez, G., 1997, *MNRAS* 285, 403
Mayor, M. & Queloz, D., 1995, *Nature* 378, 355
Mortier A., Santos N. C., Sozzetti, A., Mayor M., Latham, D., Bonfils, X., & Udry, S., 2012, *A& A* 543, A45
Morton, T. D. *et al.*, 2016 *ApJ* 822, 86
Pinotti, R., Arany-Prado, L., Lyra, W., & Porto de Mello, G. F, 2005, *MNRAS* 364, 24
Pinotti, R., Boechat-Roberty, H. M., & Porto de Mello, G. F. 2017, *MNRAS* 28, 490
Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y., 1996 *Icarus* 124, 62
Schlaufman, K. C. & Laughlin, G., 2011 *ApJ* 738, id. 177
Schneider, J., Dedieu, C., Le Sidaner, P., Savalle R., & Zolotukhin, I., 2011, *A& A* 532, A79
Sozzetti, A., Torres, G., Latham, D. W., Stefanik, R. P., Korzennik, S. G., Boss, A. P., Carney, B. W., & Laird, J. B., 2009, *ApJ* 697, 544
Yasui, C., Kobayashi, N., Tokunaga, A. T., Saito, M., & Tokoku, C., 2010, *ApJ* 723, L113