The Metallicity-Period-Mass Diagram of low-mass exoplanets

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ABSTRACT
The number of exoplanet detections continues to grow following the development of better instruments and missions. Key steps for the understanding of these worlds comes from their characterization and its statistical studies. We explore the metallicity-period-mass diagram for known exoplanets by using an updated version of The Stellar parameters for stars With ExoplanETs CATalog (SWEET-Cat), a unique compilation of precise stellar parameters for planet-host stars provided for the exoplanet community. Here we focus on the planets with minimum mass below 30 M⊕ which seems to present a possible correlation in the metallicity-period-mass diagram where the mass of the planet increases with both metallicity and period. Our analysis suggests that the general observed correlation may be not fully explained by observational biases. Additional precise data will be fundamental to confirm or deny this possible correlation.

Key words: planetary systems – planets and satellites: formation – planets and satellites: dynamical evolution and stability

1 INTRODUCTION
One of the first observational constraints for planet formation theories was the correlation between the presence of giant planets and the metallicity of their host stars where the massive planets are more common around metal-richer stars (e.g. Santos et al. 2004; Fischer & Valenti 2005). Given the known observational biases of the most successful detection methods (radial velocities and transits), that are sensible to either massive and larger planets at short periods, the first planets to be discovered were as or more massive than Jupiter with periods of only a few days. As the techniques improved with the time passed, exoplanets with masses below that of Jupiter were found, and the planet metallicity correlation was tested for neptune-like and rocky exoplanets, where, despite the very low statistical significance of the first results, the metallicity correlation seemed to be absent and not following what has been observed for their higher mass counterparts (e.g. Udry et al. 2006; Sousa et al. 2008; Ghezzi et al. 2010; Sousa et al. 2011a; Buchhave et al. 2012). Recently, Wang & Fischer (2015) suggested that there should be a universal planet-metallicity correlation for all planets, however, this result might be related to the higher planet frequency and to the lower detectability of low-mass planets (Zhu et al. 2016). Very recently Petigura et al. (2018) suggested a positive correlation of the planet occurrence rates with metallicities including small planets, except for the very small, Earth-size, planets for which the correlation seems not

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to be present. These trends are compatible with the works of Buchhave et al. (2014); Buchhave & Latham (2015). All these observational correlations provide strong constraints for the theory of planet formation and evolution.

In this work we will take advantage of a large sample of planet-host stars with homogeneous spectroscopic parameters of the Stars With ExoplanETs CATalog (see SWEET-Cat; Santos et al. (2013)). We will use the latest version of this catalogue which was recently updated in Sousa et al. (2018) and in combination with the planet properties listed in exoplanet.eu (Schneider et al. 2011) we study in detail the metallicity-period-mass diagram of exoplanets in search of observable correlations.

This paper is divided into the following sections: In section 2 we present the metallicity-period-mass diagram. In Section 2.1 we focus the discussion on the low-mass planets and report an interdependence of the parameters. In section 2.2 it is checked if multiple planetary systems may explain the result. Then in Section 2.3 we re-check the possible presence of an upper boundary in the mass-metallicity planet for low mass planets. In Section 3 we present a discussion mentioning any possible observational bias, and then considering some basic ideas for planet formation and evolution. Finally in Section 4 we summarize this work.

2 METALLICITY-PERIOD-MASS DIAGRAM

The metallicity of the host star and the period and mass of the exoplanet are explored for several exoplanets in the metallicity-period-mass diagram (MPM diagram) presented in Figure 1. The SWEET-Cat catalog is characterized for the homogeneity of the spectroscopic stellar parameters found in it, and we only considered planet-hosts with Homogeneity flag = 1. This means that the spectroscopic stellar parameters were derived using the same methodology (for more details see Sousa (2014)). To avoid finding trends that may be related to the precision on the determination of spectroscopic stellar parameters, instead of related to the physics of planet formation and evolution, we also did a cut in effective temperature. We thus only included planets for which the host star have \( \text{Teff} > 4500 \text{K} \) in the MPM diagram, given that the spectroscopic stellar parameters are less precise for the cooler stars (\( \sigma_T > 0.1 \text{ dex in } [\text{Fe/H}] \), e.g. Rojas-Ayala et al. (2012); Mann et al. (2013); Onehag et al. (2012)). A total number of 782 exoplanets are included in the MPM diagram. In the right panel we also show the period distributions of the exoplanets, where we divided the sample in two by exoplanet mass, labelling as High-Mass Planets (HMP’s - 655 exoplanets) the ones with minimum masses...
greater than 30 $M_\oplus$ ($\sim 0.095 M_J$), and Low-Mass Planets (LMPs - 127 exoplanets) the ones with minimum masses less or equal to 30 $M_\oplus$. The value of 30 $M_\oplus$ comes from the location of the gap in the planet mass distribution presented in Mayor et al. (2011) and we keep this value to separate in mass the samples to be consistent with our previous works (e.g., Sousa et al. 2011b). Note that we have also considered a separation at 20 and 40 $M_\oplus$ however no significant changes were seen with these different values to cut into two different distributions.

The division of the sample in two groups by exoplanet mass reveals three populations of exoplanets in the distribution of periods. The HMPs distribution shows 2 peaks at different periods: one corresponds to the very well known “hot Jupiters” population with the peak in period around 3 days (e.g., Dawson & Johnson 2018), and the second corresponds to Jupiter-like planets at longer periods. This last one presents a wider dispersion of periods with a peak close to 1000 days.

The short period peak followed by a “valley” in the period distribution of giant planets has already been identified and discussed in several works (e.g. Dawson & Johnson 2018). Observational bias could be responsible for the existence of the “valley” given that the hot Jupiters are mainly discovered by transits, while the jupiter-like planets are detected with RVs. This result was already discussed as based on older radial-velocity surveys (Udry & Santos 2007). Despite the strong bias of the transit technique to detect shorter period planets, recent results have also confirmed that such trend exists in Kepler data. For example, Fig. 8 of Santerne et al. (2016) shows a very similar picture stating that although this peak of hot-Jupiters was not confirmed in previous analysis of Kepler data, it reveals itself once the false positives are removed from the Kepler data.

The LMPs distribution is located in between these two populations of HMPs. We will focus our discussion in the distribution of LMPs from now on.

### 2.1 The low-mass exoplanet distribution

The observed distribution of the LMPs in Figure 1 seems to be different from the HMPs: the LMPs preferentially occupy the gap of space between the two peaks of the HMPs distribution. Due to detectability limits, we are not able to have a complete picture of the period distribution of LMPs at longer periods, but it is evident that this population will be different anyway, given that the HMPs with periods of 10-100 days can be detected easily by RV surveys, but they are under represented in the HMPs distribution. Also the fact that low mass planets have a different distribution (for short periods) than giant planets has already been discussed in other works (e.g. Boné et al. 2012).

In this work we will focus on the detected LMPs whose period distribution appears to be quite disperse, without a clear maximum in its distribution as seen in Figure 1. Note however that we are not claiming here that the real LMP period distribution is flat. To recover the real (biases corrected) period distribution of low mass planets one need to consider very carefully all the detection limits coming from the different detection surveys, which is out of the scope of the current study. The reason for the apparent (visual) flat distribution might be due to the small sample size of the LMPs and at some level to the relative scale of the figure where the LMPs and HMPs period distributions are shown together.

Note however that when we remove the constraint for LMPs listed in SWEET-Cat with Homogeneity flag = 1 the period distribution appears different with a clear peak around 10 days. This peak at 10 days is most likely linked with transit observation bias which favour the detection of short period planets. Note also that many of these LMPs were detected by transit surveys (e.g. Kepler mission) which target many faint stars. Because of this SWEET-Cat does not have an homogeneity flag of 1 (i.e., they were excluded from our analysis). The LMPs period distribution presented in figure 1, where 80 % of the planets were detected by RV surveys, is actually very close to the one presented in Figure 14 of Mayor et al. (2011) when considering only RV detections for a specific survey. In the same figure of Mayor et al. (2011) we can see how the real period distribution of LMPs is affected when considering detection limits.

Focusing on the LMPs with homogeneously derived stellar metallicities, we present a zoomed-in version of the PM distribution where only reliable LMPs are included. Therefore, in Figure 2 we only include planets with planetary masses derived with an absolute precision better than 6 $M_\oplus$, i.e. below 20% accuracy for a planet at the threshold of 30 $M_\oplus$. This absolute precision constraint allows to keep 103 LMPs. We choose this approach because when constraining the sample with a relative precision (e.g. 20%) we were removing several very low-mass planets with slightly higher uncertainties but which are for sure LMPs with masses below 30 $M_\oplus$. Figure A1 presents the 3-dimensional errors for each LMP in the sample.

A gradient in mass is observable going from the lower mass LMPs (yellow points) in the metal-poor regime (left side of the diagram) to the most massive LMPs (orange/red
points) on the metal-rich regime (right side of the diagram). To make it more visible in Figure 2 the background color represents a binned averaged planetary mass which is computed using an implementation of a boxcar average in 2D. This representation shows a planet mass dependence not only on metallicity but also on the period of the planets. The masses of the LMP sample seems to grow with the increase of the metallicity of the host star and with the increase of their orbiting period. To quantify the level of dependence of the visual correlation in the data, we performed a 3D plane fit to the data considering the errors for all the variables (see Appendix A for more details about the fitting method and respective references). The coefficients that we find when fitting this data are the following:

\[ M_p = (5.3 \pm 0.2) + (12.0 \pm 0.5) \cdot [\text{Fe/H}] + (4.0 \pm 0.2) \cdot \log(P) \]  

(1)

where \(M_p\) is the mass of the planet, \([\text{Fe/H}]\) is the metallicity (in dex) and \(P\) the period of the planet (in days). In Figure 2 we also show this fit when fixing the mass to 10 \(M_\oplus\) for a better visual representation of the correlation. In Section 3 we discuss in detail possible interpretations of this correlation and possible observational biases which can be in play.

2.2 Multiple planetary systems with low-mass exoplanets

The effect of planet-planet interactions can definitely affect the evolution of the formed planets in multi-planetary systems. Massive Jovian planets specially certainly have major impact on the dynamics of the small planets in the systems (e.g. Kobayashi et al. 2012; Becker & Adams 2017; Munoz Romero & Kempton 2018). A significant part of the analysed LMPs are indeed in multi-planetary systems (only 22 out of 127 LMPs and 16 out of 84 LMPs, are currently single in Figure 1 and 2, respectively). For the metal-rich regime, it is reasonable to consider that the presence of massive planets in the system, preferably found in short (3-day) and long (1000 day) periods, may have a strong impact on the dynamics of the systems, affecting the orbital evolution and the observed periods of the LMPs in multi-planetary systems. This could introduce an effect on the MPM correlation that we described in the previous sections.

To check for this sort of bias, we looked at two subsamples of the LMPs. The first subsample is composed of LMPs which are in single-planet systems or for which all the planets in the system have masses below 30 \(M_\oplus\). The second subsample are the rest of the LMPs which have at least one massive planet as companion on their multi-planetary systems. If planet-planet interaction plays a role in the observed correlation, the two subsamples are expected to show significant differences in the MPM diagram. Interestingly, this analysis has shown that there are no significant changes in the trend in the MPM diagram after the removal of the LMPs with massive companions, and the least-square fitting returns similar coefficients when compared with the ones in equation 1.

For the second sample, which contains only the LMPs with massive planets in their multi-planet system, we use a slightly different representation. There are only 22 LMPs (26% of all LMPs) in the second sample and they are shown in the metallicity-period diagram of Figure 3. The planets of the same system are connected with distinct vertical lines for clarity. The LMPs are represented with ‘x’ while the giant/massive planets are represented with a semi-transparent circle, which size is proportional to their planetary mass. Given the metallicity correlation of massive exoplanets, these systems are preferentially found around metal-rich stars, and, hence, we do not have many systems at low metallicity in our second sample. Although the number of these systems is small, these systems have preferentially their LMPs in shorter periods when compared with the massive planet companions. This is specially evident at higher metallicities. In a different perspective, our sample shows that Hot Jupiters are unlikely to have LMPs detected in relatively short periods (at least where the LMPs can be detected). In fact, there is only one Hot Jupiter (P < 10 days) at the right part of Figure 3 (WASP-47b). This is consistent with previous results in what regards Hot Jupiters, since it is known that they are mostly alone on their planetary systems (Steffen et al. 2012; Huang et al. 2016; Schlaufman & Winn 2016).

Since the two sub-samples do not show significant changes in the MPM diagram we can deduce then that the dynamics of multi-planetary systems do not have a measurable effect on the mass-metallicity-period dependence. The discovery of new low-mass planets with precise characterization will certainly help in confirming this observational result.

2.3 An upper boundary in the mass-metallicity exo-Neptunes

A possible upper boundary in the mass-metallicity of exo-Neptunes was proposed by Courcol et al. (2016). This upper boundary, if real, could give important constraints for the formation of LMPs assuming that the metallicity is a key parameter for the maximal mass of these small planets. Al-
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3 DISCUSSION

3.1 Observational bias

Observational bias of the detection methods to find exoplanets could play an important role in the interdependence of the parameters that we observe here in the MPM diagram, specially when focusing on low-mass planets. The vast majority of these LMPs are detected with the radial-velocity technique (99/127 in Fig. 1 and 60/84 in Fig. 2), where the higher the mass of the planet, the easier it is to detect it. This could partially explain the dependence on the mass with the period that we is present in the diagram.

On the metallicity dependence in the diagram, we know that the metallicity has a small impact on the radial-velocity detections (see e.g. Figure 8 of Valenti & Fischer 2008). However when looking carefully at our sample there is another relevant dependence with metallicity which has a direct impact on the RV detection technique. The stars hosting LMPs have a stellar-mass vs. metallicity correlation, where the most metallic hosts are more massive than the metal-poor hosts. In the top panel of Fig. 5 we plot the same kind of MPM diagram, but exchanging the planet mass by the host stellar mass. The background color is the box car average of the stellar mass, and the dashed line marks a linear fit for a constant stellar mass of 0.9 $M_\odot$. This dependence will also affect the detection of the lower mass planets, specially for the metal-rich stars in our sample. At this point there are two interesting questions that can be raised. The first is: Are these LMPs host stars different from typical stars? And, can this correlation be enough to explain the interdependence that we see in the data for the MPM diagram?

To answer the first question, we compared our sample of LMPs host stars against a sample of 1111 stars located in the solar neighborhood taken from the HARPS sample discussed in Adibekyan et al. (2012). In fact in Sousa et al. (2018) we already compared this solar neighborhood sample against the full sample of LMPs host stars showing that in what regards the metallicity distribution they are in fact indistinguishable. Now, when comparing the distribution of the stellar mass in the samples we also do not see any significant differences, specially given the small number of LMPs host stars. Performing a Kolmogorov-Smirnov (K-S) test on both samples we obtain K-S statistic of 0.15 and a p-value of 7.95e-02. And if we select only the metal-rich stars from these samples ([Fe/H] > 0), i.e. for the MPM region where we are "missing" the less massive LMPs), we see a K-S statistic of 0.16 and a p-value of 1.66e-01. Therefore we can conclude that as we see for metallicity, here we also don’t see any relevant difference between the stars hosting LMPs and the neighborhood stars in what regards the stellar mass. It is still reasonable to point out the average and standard deviation of the masses that we have at low and high metallicities. For metal-poor stars ([Fe/H] < 0) from the neighborhood sample we see the average stellar mass of 0.87 ± 0.17 $M_\odot$ while for the metal-rich stars we have an average stellar mass of 1.02 ± 0.18 $M_\odot$. Although the average is significantly higher, the standard deviation shows that we can still have stars with relatively low mass at higher metallicities, and for which we could detect lower mass planets with the current instrumental limitations.

This last statement partially answers the second question. However to be more focus on our sample of LMPs, we choose to plot on the bottom panel of Figure 5 the RV semi-amplitude for all the LMPs in our sample. The RV semi-amplitude was estimated in the same way for all the LMPs since it was not reported in exo.eu for a non negligible number of exoplanets. These values were then estimated using the stellar masses, the minimum planetary masses, the orbital period and the eccentricities (where we assumed zero when it was not available in exo.eu). As for MPM dia-

Figure 4. Planetary mass vs. the metallicity. This is a reproduction of the top panel of Fig. 3 of Courcol et al. (2016) with updated SWEET-Cat data. Dashed line corresponds to the proposed upper boundary on the same work. The color scale represents the period (days) of the planets in logarithm scale.

Figure 5. Planetary mass vs. the stellar mass. The background color is the box car average of the stellar mass, and the dashed line marks a linear fit for a constant stellar mass of 0.9 $M_\odot$. This dependence will also affect the detection of the lower mass planets, specially for the metal-rich stars in our sample. At this point there are two interesting questions that can be raised. The first is: Are these LMPs host stars different from typical stars? And, can this correlation be enough to explain the interdependence that we see in the data for the MPM diagram?
Figure 5. Same as Figure 2 but the color scale represent the stellar mass (top panel) and the RV semi-amplitude (bottom panel). The dashed line represents the linear fit for a constant value, $0.9 \, M_\odot$ and $4 \, m/s$ on the top and bottom panels respectively.

gram in figure 2 we also use a box car average for the background color for a better visualization. A linear fit was also performed to this figure, where the dashed line mark the line where we have a RV semi-amplitude of 4 m/s. From the figure it is clear that for the planets around metal-rich stars, these have on average higher semi-amplitude when compared with the metal-poor host stars, meaning that in fact we would be able to detect less massive planets in this region of the MPM. This means that although there is a clear observational bias, both for period, and metallicity, it is probably not enough to explain the lack of very-low mass and detectable planets in the metal-rich region of the MPMs. Therefore, it is difficult to explain a mass-period-metallicity dependence only by these observational bias.

One final note on observational bias that we would like to mention is related with stellar activity. Given that the RV semi-amplitudes are larger for metal-rich stars we also consider the possibility that the stellar activity, for some reason, would be greater for the metal-rich stars, and could pull the RV limits to lower precision. However, to check this carefully we would need to go star-by-star to check individual stellar activity. Moreover, this issue should be very unlikely to be a problem. From one side, the RV planet-search samples are already very conservative in what regards stellar activity, and we remind the reader that the large fraction of these planets were detected by RV. On the other side, the stellar activity is not always a problem for the planet detection, since the planetary signals are in many of the cases completely disentangle from the stellar activity signal, specially for the cases where the stellar rotation period is significantly different from the planet orbital period.

3.2 Correlation by chance?

So far we have discussed several observational biases that can affect the correlation that we present in this work. In the last section we refer to a few observational biases which can affect the correlation presented in Fig. 2. In this section we try to quantify the effect of these observational biases, or in other words, estimate the probability that the observed correlation is obtained by chance.

To address this question we performed Monte-Carlo simulations to statistically represent the MPM diagram based on the following assumptions:

- The simulated hosting star (stellar mass, and stellar [Fe/H]) is randomly selected from the HARPS sample discussed in Adibekyan et al. (2012). For each star we assume a Gaussian error for its mass and metallicity (10% in mass and 0.05 dex in metallicity). This way we are keeping the stellar mass and stellar metallicity distributions that we have for the solar neighborhood including the correlation between these two variables. Note again that the metallicity distribution of LMPs is basically indistinguishable from the solar neighborhood stars metallicity distribution;
- The planet minimum mass is selected from a uniform distribution between $0.25$ and $30 \, M_\oplus$;
- The planet logarithmic period is selected from a uniform distribution between $0$ and $2.2$ (1 day and $\sim 160$ days - the range of periods observed in Figure 2). With this we are ensuring that the distributions of the points in the MPM diagram will be very similar to the one that we have for the real data;
- For the estimation of the RV semi-amplitude we assume planet with eccentricity $0$.

We then did 1000 random draws from these distributions and for each resulting star-planet system we computed the expected semi-amplitude of the radial velocity signal. Only planets producing an RV semi-amplitude above $1 \, m/s$ were selected. This is the typical RV precision that we have in many RV surveys (e.g. using HARPS). Each simulated sample had 100 points in order to be consistent to the size of the real data.

These assumptions allow to generate data considering the most important observational bias discussed in the previous section. For each randomly generated sample we then used the same 3D fitting method to extract the correlation slopes ($m_1$ - slope for [Fe/H] in units $[M_\oplus/dex]$, and $m_2$ - slope for log(period) in units $[M_\oplus/dex]$) for each simulation and compare the slopes distributions to the slopes derived for the real data. The goal is to try to estimate the probability that the slopes obtained for the real data could come by
chance. An example of the MPM diagram for one of these simulations is presented in the top panel of Figure B1.

In figure 6 we present the distributions of the slopes m1 and m2 obtained for our simulations. The average slope m1 is $1.20 \pm 8.43 \ [M_\odot/dex]$ and the average slope m2 is $3.21 \pm 1.38 \ [M_\odot/dex]$. From the respective distributions we can state that the metallicity correlation (m1) due to the observational bias seems to be very small, but with high uncertainty. The slope that we obtain for the real data (12.0 $[M_\odot/dex]$) is outside the one sigma standard deviation, making it unlikely to retrieve this value by chance under our assumptions. In what regards the period correlation (m2), the expected correlation due to observational bias seems to be quite high and more precise when compared with m1. The value (4.0 $[M_\odot/dex]$) that we get for the real data is within one sigma. Therefore we cannot exclude the possibility that the period correlation found in the real data could indeed be entirely due to the assumed observational bias.

A similar exercise was also done to check the 3D fits when using the RV semi-amplitudes instead of the planetary masses for the simulated data (see bottom panel of figure B1). From the simulations these slopes distributions show an average slope m1 of $-2.19 \pm 2.59 \ [m/s/dex]$, and an average slope m2 of $-3.82 \pm 0.59 \ [m/s/dex]$. These slopes better represent and quantify the expected observational biases due to RV detection limits. Interestingly for the real data presented in the bottom panel of figure 5 we obtained m1 = 3.62 \pm 0.45 \ [m/s/dex]$ and m2 = -0.71 \pm 0.19 \ [m/s/dex]$. Both these slopes are unlikely to be derived by chance.

With these simulations we show that it is unlikely to find the presented general 3D correlation by chance. However some caution should be taken when considering the period correlation. Additional precise data will be fundamental to confirm or infirm this possible interesting correlation.

### 3.3 Clues for planet formation and evolution

There is plenty to learn in what regards the formation and evolution of planets. Several theoretical mechanisms in the literature can be used to explain the observations. How does our observed mass-period-metallicity dependence on LMPs fit in some of the most trending theoretical ideas?

The migration of planets is a theoretical mechanism quite discussed in the literature that should act more efficiently on massive planets, given that the mass of the planet have a direct impact on the size of the gap in the circumstellar disk, affecting directly the time scale of migration (Lubow & Ida 2010; Baruteau et al. 2016). If we consider migration for the LMPs, this could be somehow compatible with the correlation that we observe in the MPM diagram. These LMPs are dispersive in period, but their mass and metallicity of the system seem to play a role in the final position of their orbits. We could consider that the planet mass can slow down the effect of migration. But if migration is the only mechanism in play, the observed trend tells us that metallicity would also affect the migration. The higher the metallicity the longer should be the time scales for migration, allowing for the more massive LMPs to be closer to the star for higher metallicity environments.

In-situ formation for LMPs (e.g. Chiang & Laughlin 2013) can be another mechanism to explain the dependence that we present here. Simply considering the assumption of an homogeneous formation disc, we would expect the observed mass-metallicity-period correlation. The increase of metallicity would mean higher presence of the fundamental building blocks to form the planets. The closer the formation site (radius/period) is to the star, the less quantity of condensed material closer to the star will be available to form the planet. Therefore, for shorter periods, we would have lower mass planets, just like we observe in Figure 2.

A combination of these two effect could also be at play. One certain remains, that with the still low number of low-mass planets with precise masses detected and the several observational bias that can be in place, it is clear that we need more detection of LMPs to better understand and quantify this MPM interdependence.

### 4 SUMMARY

We use the recently updated version of SWEET-Cat to exploit the metallicity-period-mass (MPM) diagram of known exoplanets. In the diagram the detected exoplanets are clustered in three groups: the well known hot-Jupiter population; a population of jupiter-like massive planets at long periods; and a low mass planet population. We focus our work on the detected low-mass planet population that have periods in between the previous two massive planet populations.

We found a dependence of the mass of low-mass planets on the metallicity and the period, which is close to linear, correlating both with the metallicity and the logarithm of...
the period. The mass of the planets increases for metal richer stars and for longer periods.

Although the dynamics of multi-planetary systems influences the architectures of planetary systems, a very simple test was performed looking at two subsamples of planetary systems (only low mass planet systems vs low mass planet with massive companion) revealing no significant differences in the observed MPM dependence.

We also review the proposed upper boundary in the mass-metallicity plane of exo-Neptunes proposed by Courcol et al. (2016). We show that there are some new low-mass planets above the proposed line, but more data is required to better define the possibility of this upper boundary.

The possible correlation observed in the MPM diagram, can be strongly affected by observational biases, but we show that these biases alone cannot entirely explain the general interdependence observed in the MPM diagram. More precise data will be fundamental to confirm this possible interesting correlation which can provide important constraints to the theories of planet formation and evolution.

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APPENDIX A: FITTING THE MPM DIAGRAM

The 3D plane fitting was done using an MCMC approach following very closely and adapting the Python implementation presented in https://dfm.io/posts/fitting-a-plane/ which is based on Chapter 7 of Hogg et al. (2010). Using this method we are able to use errors for all the variables and provide reliable errors estimations for retrieved coefficients using the data presented in Figure 2.

The general plane equation used to fit the data on the MPM diagram is written as:

\[ M_p = b + m_1 \times [Fe/H] + m_2 \times \log(P) \]  

(A1)

where \( M_p \) is the mass of the planet, \([Fe/H]\) is the metallicity (in dex), \( P \) the period of the planet (in days), \( m_1 \) and
m2 are the slopes of the correlations and b is the constant value at the origin.

APPENDIX B: SIMULATED MPM DIAGRAM EXAMPLE

This paper has been typeset from a \TeX/La\TeX file prepared by the author.
Figure A1. Data of Figure 2 with respective errors.
Figure A2. Samples to estimate the fitting coefficients of the plane correlation. This figure was produced using corner python module (Foreman-Mackey 2016).
Figure B1. Same as Figure 2 but for one simulated data (top panel) and the RV semi-amplitude (bottom panel). The dashed line represents the linear fit for a constant value, 10 $M_\oplus$ and 4 m/s on the top and bottom panels respectively.