Planetary Orbit Eccentricity Trends (POET). I. The Eccentricity-Metallicity Trend for Small Planets Revealed by the LAMOST-Gaia-Kepler Sample.

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1.Background

Orbital eccentricity is one of the basic planetary properties, whose distribution may shed light on the history of planet formation and evolution. Some exoplanets with eccentricities different from the solar system have been found since 1995, which inspires us to think about whether this eccentricity distribution is widespread and how they depend on stellar and planetary properties. With more than 5200 exoplanets found, with surveys of spectroscopy, e.g., APOGEE, CKS, and LAMOST, and of astrometry, e.g., Gaia for their hosts. Here, in a series of works on Planetary Orbit Eccentricity Trends (dubbed POET), we study the distribution of planetary eccentricities and their dependence on stellar/planetary properties.

2.Motivation

Among various stellar properties, metallicity is a crucial factor in planet formation and evolution which may also influence the orbital architecture of a planetary system, e.g., eccentricity. Both Dawson & Murray-Clay (2013) and Buchhave et al. (2018) found that giant planets (e.g., Jovian planets) in eccentric orbits are preferentially residing with metal-rich stars. However, the situation is still unclear for small planets, e.g., super-Earths and/or sub-Neptunes (Van Eylen et al. 2019 ;Mills et al. 2019). In this paper, the first work of the POET series, we investigate whether and how the eccentricities of small planets depend on stellar metallicities (e.g., [Fe/H]).

Table 1
Summary of the Sample Selection

	Host star (Number)	Planet (Number)
Kepler DR25	6923	8054
Not false positive	3069	4034
Match with LAMOST	1049	1409
Match with Berger et al. (2020)	995	1343
RUWE $\leqslant 1.2$	862	1166
GOF > 0.99	860	1164
Main sequence ($\log g > 4$)	740	1024
4700 K $< T_{\rm eff} <$ 6500 K	638	899
S/N > 7.1	632	891
Relative error of $r \equiv \frac{R_p}{R_*} < 0.3$	618	875
Single (Multiple)[a]	450 (168)	450 (424)
Disposition score > 0.9	394 (166)	394 (380)
$R_p < 4\ R_\oplus$	345 (164)	345 (362)
Period > 5 days	244 (152)	244 (286)

3.Sample Selection

We do sample selection based on **Table 1**. Finally, we have 244 single-transiting systems with 244 small planets and 152 multiple-transiting systems with 286 small planets in our sample.

4.Method

We use transit duration ratio ($\mathrm{TDR} \sim \frac{\sqrt{(1-b^2)(1-e^2)}}{1+e\sin\omega}$) to constrain the planet eccentricity (Ford et al. 2008), and follow the fitting method from Xie et al. (2016) to calculate planets' eccentricities.

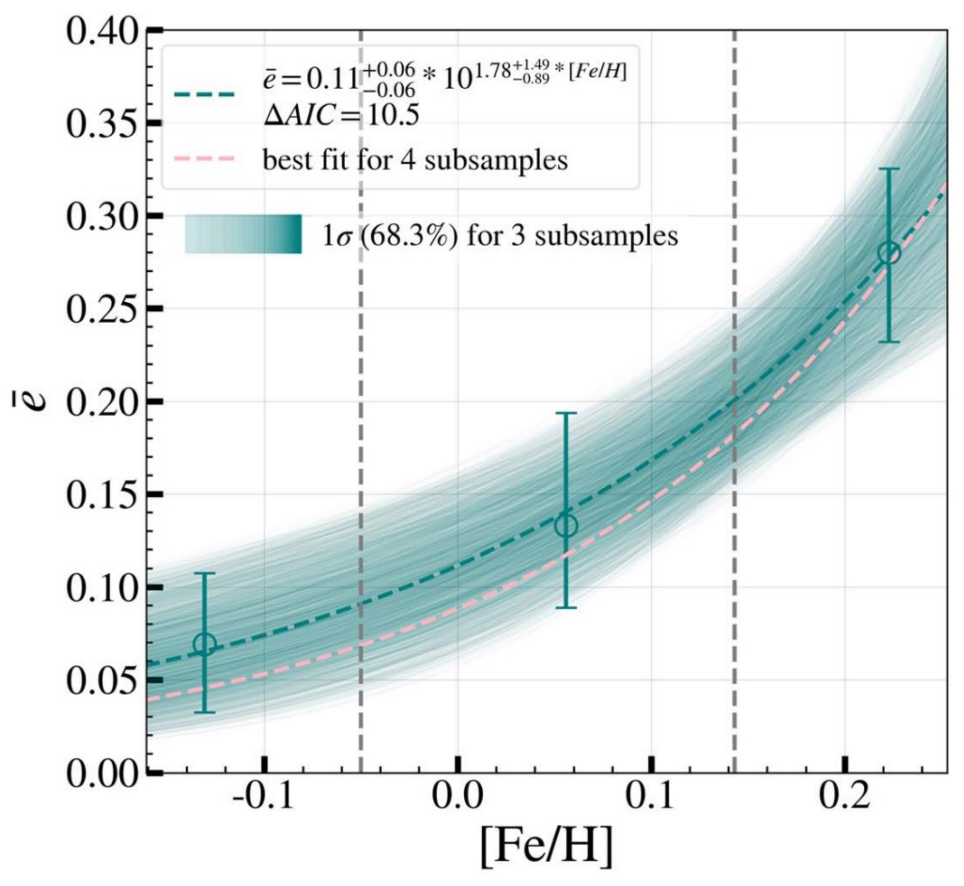

Figure 1: The the turquoise dashed line represents the exponential best fit. ΔAIC is AIC difference between the constant and exponential best fit.

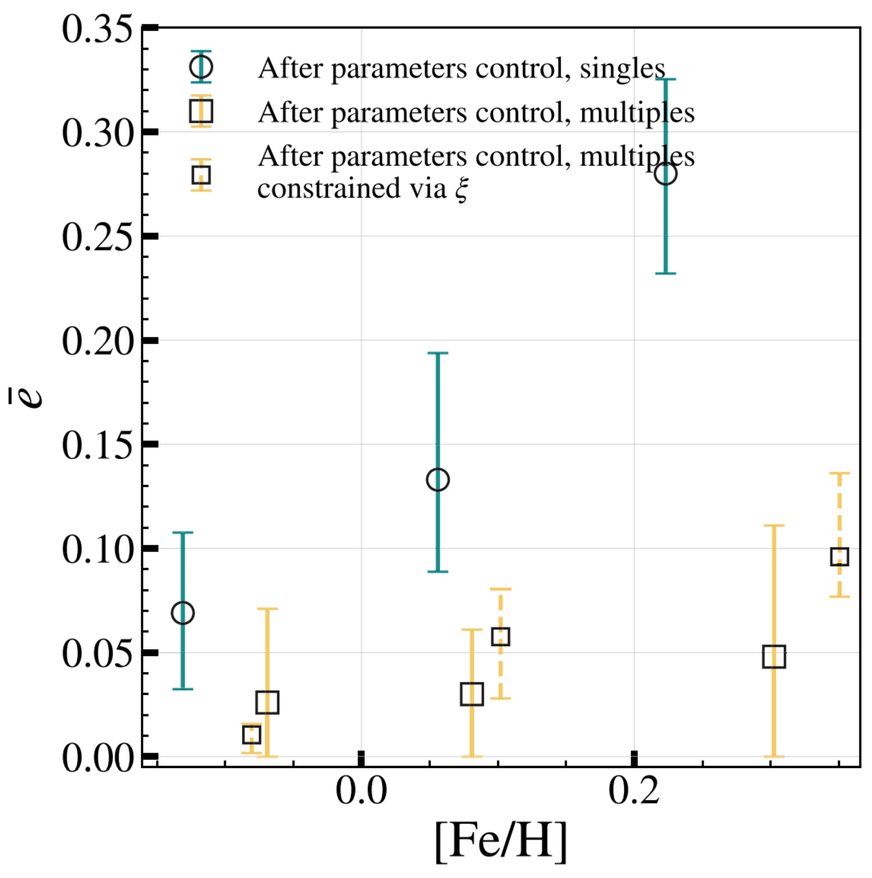

Figure 2: The mean eccentricities of singles vs. multiples under different metallicities. The solid error bars represent $\bar{e}$ constrained via TDR.

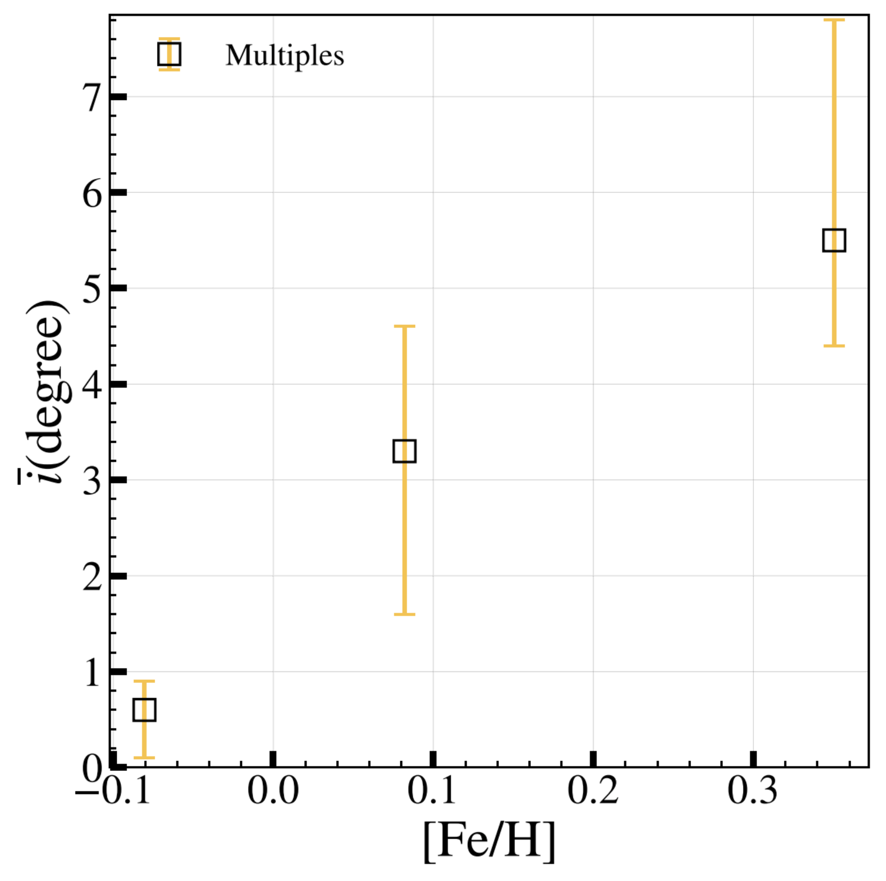

Figure 3: Mean mutual inclinations $\bar{\imath}$ of multiple transiting systems constrained by ξ distribution as a function of [Fe/H].

5.Result

- We divide our sample into three subsamples based on [Fe/H]. Then performed the TDR fitting to derive the eccentricity distribution. Results of singles are shown in **Figure 1**. We performed an AIC analysis and found the eccentricity–metallicity trend prefers the exponential model.
- **Figure 2** shows the metallicity–eccentricity trend for singles and multiples. The multiples have smaller eccentricities than the singles and the difference in eccentricity is larger for higher metallicity.
- **Figure 3** shows the metallicity – inclination trend for multiples. Although having a large uncertainty, the mean mutual inclination tends to increase with metallicity.

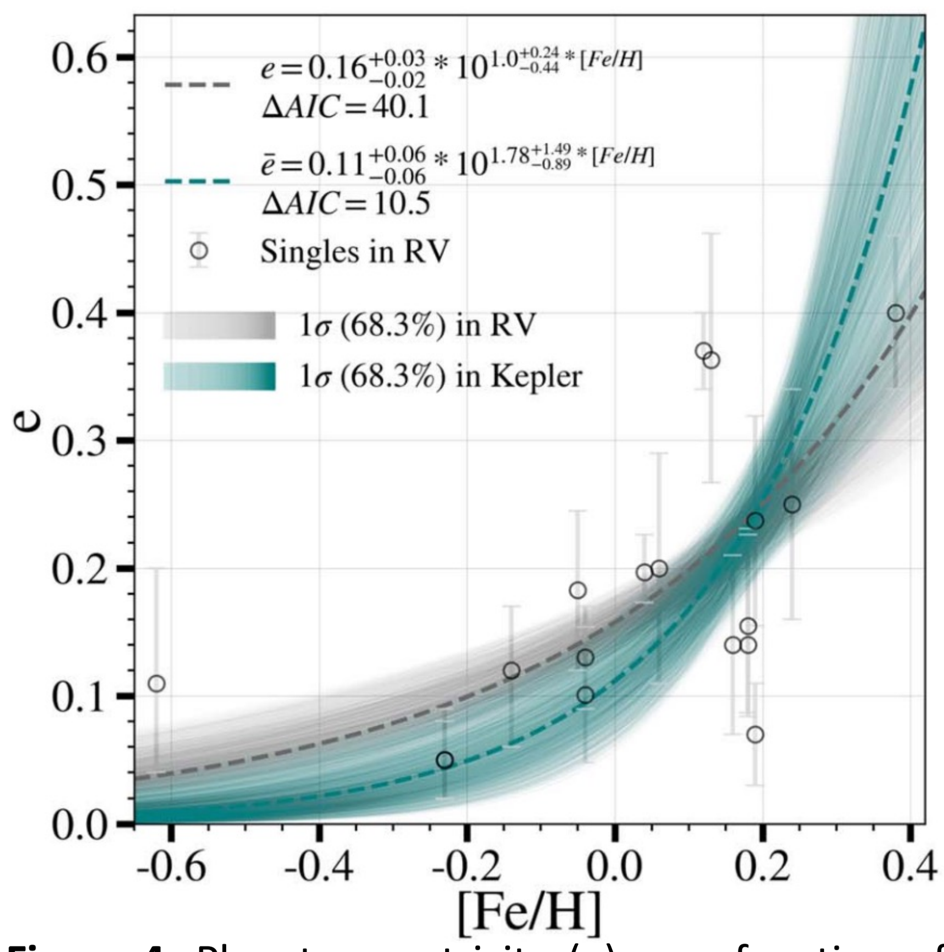

Figure 4: Planet eccentricity (e) as a function of the stellar metallicity ([Fe/H]) for single systems in the RV sample, which also prefer an exponential model and best fit is denoted by the gray dashed lines. For comparison, we also plot the best fit for Kepler singles (the turquoise dashed lines).

6.Discussion

- We compared our results with RV planet and found they are consistent within ~1σ, as shown in **Figure 4**.
- Our results are consistent with Xie et al. 2016.
- According to the N-body simulations by Moriarty & Ballard (2016), the mean eccentricities of planets increase from $\bar{e}$~0.06 to ~0.10 when the total mass of the planetesimals in the disk increases from 7 $M_\oplus$ to 35 $M_\oplus$. Such an increase in metallicity leads to an eccentricity increase from ~0.01 to ~0.12 according to our results. This result is comparable to the N-body simulation result except at the metal-poorest end.
- The eccentricities of inner small planets can be excited by outer planets (e.g. Huang et al. 2017; Pu & Lai 2018; Poon & Nelson 2020). Combining this with the well-known metallicity–giant planet correlation (Fischer & Valenti 2005), one may naturally expect a correlation between eccentricity and metallicity for small planets in single transiting systems. However, there is no outer giant in our sample.

7.Summary

- Here we start a project, POET, to investigate how the orbital eccentricities of planets depend on various stellar/planetary properties. In this work, the first paper of the POET series, we study the relationship between small planet (R_p < 4 $R_\oplus$) eccentricity and stellar metallicity with the LGK sample (Chen et al. 2021).
- We found that, in single transiting systems, the eccentricity of small planets increases with stellar metallicity.
- Furthermore, we fitted the eccentricity–metallicity trend and found it is best fitted with an exponential function. In contrast, we found that, in multiple transiting systems, the eccentricity–metallicity rising trend is less clear. Although an inclination–metallicity trend is seen in multiples.
- We then compared our results with the data from an RV sample of planets, and found they are consistent within 1σ.
- We identified two mechanisms (self-excitation and external excitation) that could potentially explain the observed eccentricity–metallicity trend. Future studies of both simulations and observations on a larger sample will further test them.

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