The Occurrence and Architecture of Kepler Planetary Systems as a Function of Kinematic Age

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Abstract

One of the fundamental questions in astronomy is how planetary systems form and evolve. Measuring the planetary occurrence and architecture as a function of time directly addresses this question. In the fourth paper of the Planets Across Space and Time (PAST) series, we investigate the occurrence and architecture of Kepler planetary systems as a function of kinematic age by using the LAMOST-Gaia-Kepler sample. To isolate the age effect, other stellar properties (e.g., metallicity) have been controlled. We find the following results. (1) The fraction of stars with Kepler-like planets ($F_{\rm Kep}$) is about 50% for all stars; no significant trend is found between $F_{\rm Kep}$ and age. (2) The average planet multiplicity ($\bar{N}_p$) exhibits a decreasing trend ($\sim 2\sigma$ significance) with age. It decreases from $\bar{N}_p \sim 3$ for stars younger than 1 Gyr to $\bar{N}_p \sim 1.8$ for stars about 8 Gyr. (3) The number of planets per star ($\eta = F_{\rm Kep} \times \bar{N}_p$) also shows a decreasing trend (~ 2–3σ significance). It decreases from $\eta \sim 1.6$–1.7 for young stars to $\eta \sim 1.0$ for old stars. (4) The mutual orbital inclination of the planets ($\sigma_{i,k}$) increases from $1.^\circ2^{+1.4}_{-0.5}$ to $3.^\circ5^{+8.1}_{-2.3}$ as stars aging from 0.5 to 8 Gyr with a best fit of $\log \sigma_{i,k} = 0.2 + 0.4 \times \log \frac{\rm Age}{\rm 1Gyr}$. Interestingly, the Solar System also fits such a trend. The nearly independence of $F_{\rm Kep} \sim 50\%$ on age implies that planet formation is robust and stable across the Galaxy history. The age dependence of $\bar{N}_p$ and $\sigma_{i,k}$ demonstrates planetary architecture is evolving, and planetary systems generally become dynamically hotter with fewer planets as they age.

Introduction

Thanks to various surveys from ground and space the number of known planets has reached a milestone of more than 5,000. Such a rich planetary database has enabled substantial statistical studies of the occurrence rate and architecture of planetary systems. Theoretical works have predicted the age dependence of various planet properties, such as orbital eccentricity, orbital spacing, and multiplicity. In the fourth paper of the Planets Across Space and Time series (PAST IV), we study the occurrence and architecture of Kepler planets as a function of stellar age.

Parameter Control Method

Based on the LAMOST DR8, Gaia DR3, and Kepler DR25 catalogs, we conduct a sample of 19,358 stars and 641 planets. We group the stars into 5 bins according to their *TD/D* [1]. To isolate the effect caused by stellar age, we use parameter control method to reduce the influences induced by other stellar properties. In this work, we control five properties: effective temperature, mass, metallicity, stellar radius, and $\sigma_{\rm CDPP}$. The former three parameters need to be controlled because they are found to affect the intrinsic planet occurrence rate. The latter two also need to be controlled because they directly affect the detection efficiency of transiting planets.

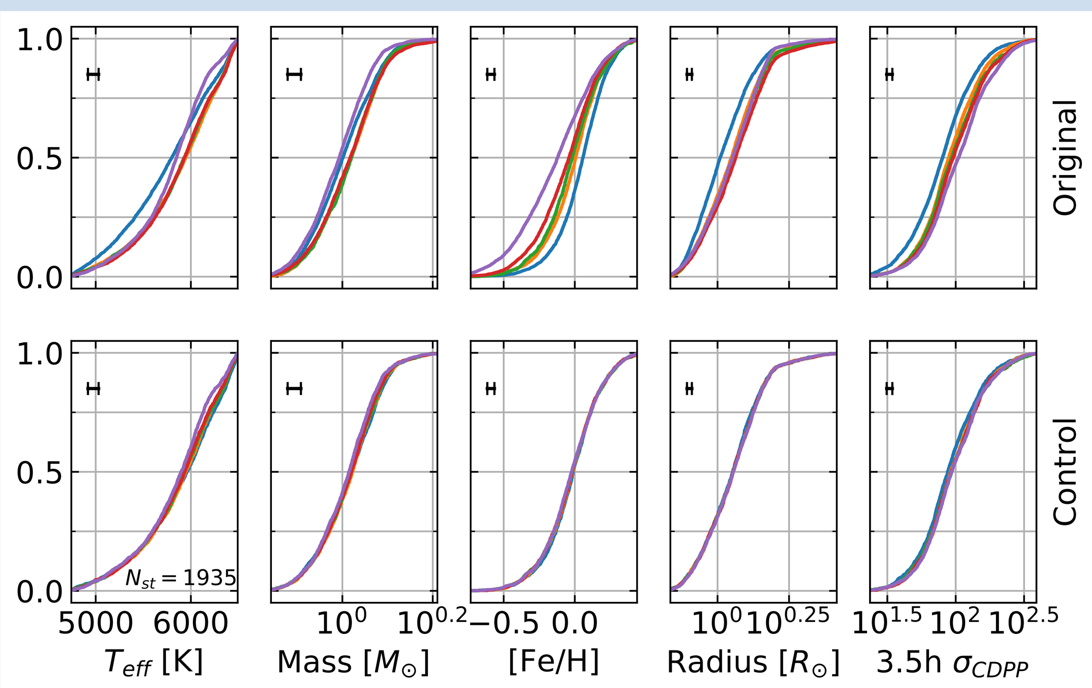

***Figure 1**: CDF diagrams of stellar properties before and after parameter control.*

By applying the parameter control method, we have achieved the goal to let stars in different age bins have similar distributions in all these five stellar properties.

Intrinsic Occurrence Rate

We apply a forward modelling method[2,3] to derive the intrinsic planet occurrence rate. Details of the modelling can be seen in Zhu et al. 2018 and Yang et al. 2020.

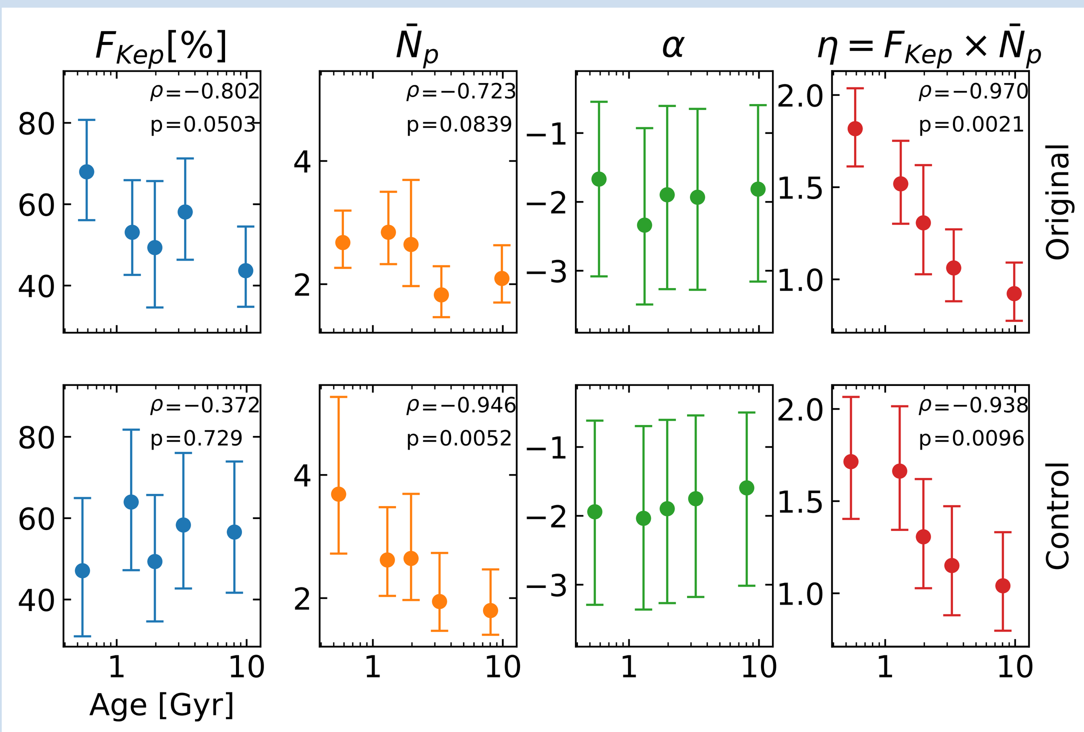

***Figure 2**: Intrinsic occurrence rate before and after parameter control.*

After parameter control (bottom row of Figure 2), $F_{\rm Kep}$ is $47.1^{+17.9}_{-16.1}\%$ for stars less than 1 Gyr, which is 0.6σ lower than stars around 8 Gyr ($56.6^{+17.4}_{-14.9}\%$). As to $\bar{N}_p$ and η, they are $3.69^{+1.58}_{-0.96}$ and $1.71^{+0.35}_{-0.31}$ for stars in the first bin, which are 2.3σ and 2.2σ higher than the values ($1.80^{+0.67}_{-0.39}$ and $1.04^{+0.29}_{-0.24}$) in the last bin. The α is not well constrained.

The anti-correlation between age and $F_{\rm Kep}$ becomes statistically insignificant after parameter control with a *p*-value of 0.729, hinting the planet system occurrence remains at a similar rate throughout the history of the Milky Way. For $\bar{N}_p$ and η, the anti-correlations between age and them are strong with *p*-values of 0.0052 and 0.0096, respectively. This result is consistent with theories that planet systems keep evolving as a result of the merging and ejecting of the planets.

Mutual orbital inclination

$\bar{N}_p$ is related to the orbital inclination (Equation 1). We can investigate the mutual orbital inclination as a function of time, and show the distribution of $\sigma_{i,k}$ in Figure 3.

$$\sigma_{i,k} \equiv \sqrt{\langle \sin^2 i \rangle} = \sigma_{i,5} \left(\frac{k}{5}\right)^{\alpha} \qquad (1)$$

Mutual orbital inclination

As we can see, $\sigma_{i,k}$ evolves gradually with time. From less than 1 Gyr to about 8 Gyr, the median $\sigma_{i,k}$ grows from about $1.^\circ2$ to $3.^\circ5$, and the 1σ range expands from $0.^\circ7$–$2.^\circ6$ to $1.^\circ3$–$11.^\circ7$. For comparison, we also plot our Solar System (red star) and Kepler multiple transiting systems (green and purple stars[4,5]) in Figure 3. This result indicates as planet systems get older, they become dynamically hotter, which is consistent with the theoretical expectation[6]. Both our Solar System and Kepler multiple transiting systems fit such a trend.

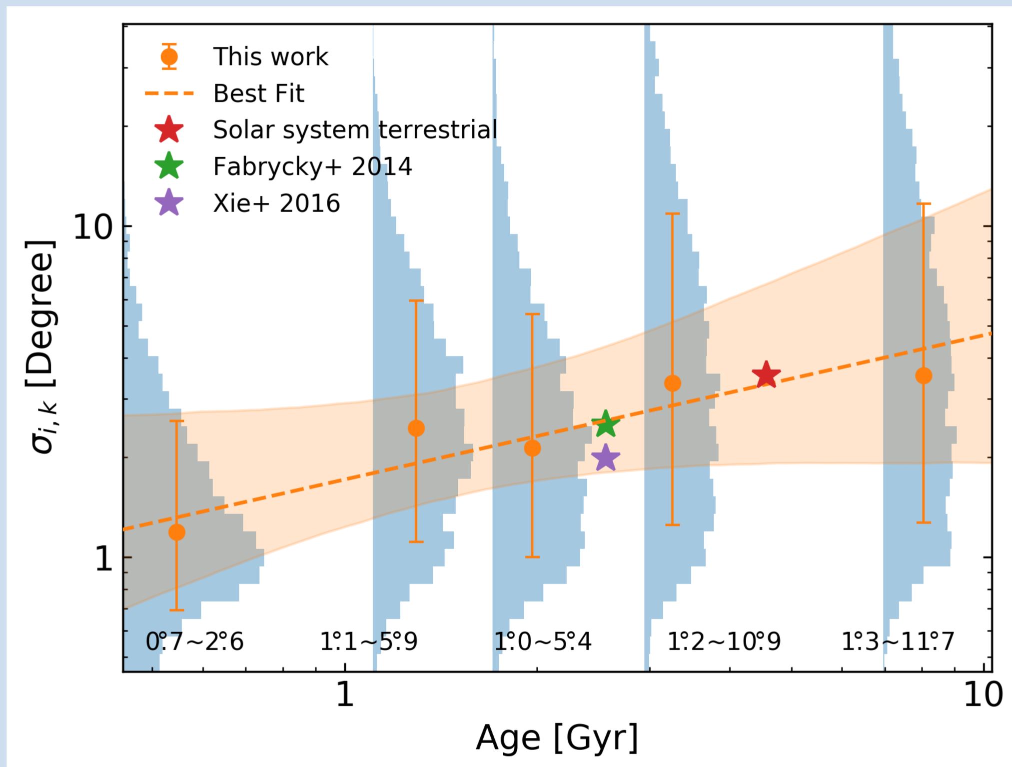

***Figure 3**: Inclination dispersion ($\sigma_{i,k}$) as a function of age.*

To further quantify the age-$\sigma_{i,k}$ trend, we fit $\sigma_{i,k}$ with age. Although bearing large uncertainty (as seen from the orange shaded region), the best fit is

$$\log \sigma_{i,k} = 0.2 + 0.4 \times \log \frac{\rm Age}{\rm Gyr}. \qquad (2)$$

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