Planets Across Space and Time (PAST) III. Morphology of the Planetary Radius Valley as a Function of Stellar Age and Metallicity

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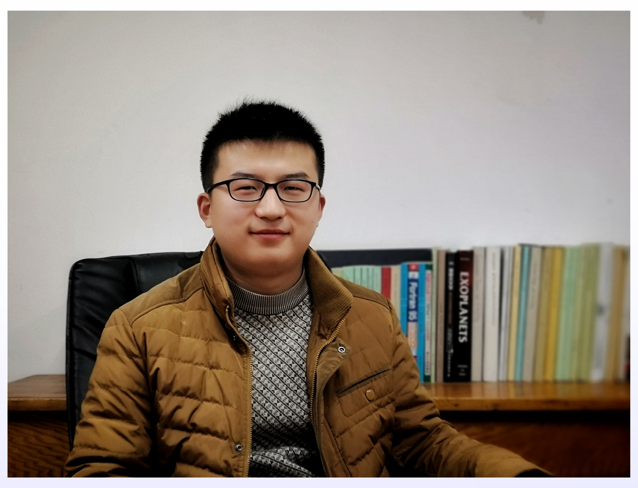

Abstract

Over 5,000 exoplanets have been identified and thousands of candidates are to be confirmed. What are the differences between planetary systems in different Galactic environments, and how do they evolve with time? To address these questions, we conduct a research project, dubbed Planets Across Space and Time (PAST). Here we present some first results of PAST series. We revisit the kinematic method for classification of Galactic components and extend the applicable range from ~ 100 pc to $\sim 1{,}500$ pc from the sun in order to cover most known planet hosts. Furthermore, we revisit the Age-Velocity dispersion Relation (AVR), which allows us to derive kinematic age with a typical uncertainty of 10-20% for an ensemble of stars. Applying the above revised methods, we present catalogs of kinematic properties as well as other basic stellar parameters for 2174 host stars of 2872 planets and 35,835 Kepler stars. Using the above kinematic catalogs, we perform a systematical investigation into the planetary radius valley morphology in the Galactic context, i.e., thin/thick galactic disks, stellar age and metallicity abundance ([Fe/H] and [α/Fe]).

Introduction

Since the discovery of the first exoplanet in 1990s, our knowledge of exoplanets is expanding in the Galaxy. Now, the map of exoplanets is much wider with a large range of distance up to $\sim$ 10,000 pc and spread over different Galactic environments, opening up the study of exoplanets in the Galactic context.

The geometry, kinematic and chemical abundance of different components vary considerably. Thus what are the differences in the properties of planetary systems at different positions in the Galaxy with different ages? The answer will provide insights on the formation and evolution of the ubiquitous and diverse exoplanets.

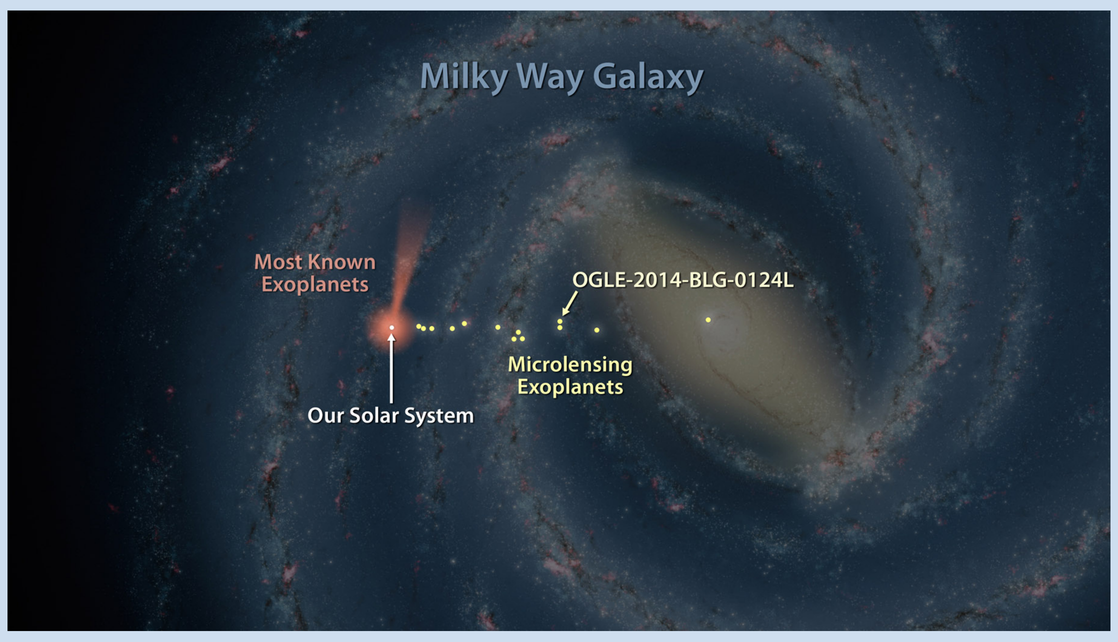

***Figure 1**: Map of exoplanets in the Milky Way.*

To address the question, the basis is to characterize the Galactic components and age of exoplanet host stars. One of well-established methods to distinguish Galactic components is the kinematic approach by comparing the kinematic properties of a given star to the typical kinematic characteristics of a Galactic component. However, the kinematic characteristics were limited in the Solar neighborhood within ~ 100 pc. The stellar age can be estimated statistically from Age-Velocity dispersion Relation (AVR) with stellar kinematics. However the derived uncertainties in kinematic age is relatively large ($\sim 30\% - 60\%$), insufficient to carry out precious age evolution studies.

Revise kinematic methods

To characterize the planet host stars, we conduct a calibration sample of 130,403 stars with kinematics and age data based on the LAMOST DR4 and Gaia DR2 catalogs, and then revise the kinematic methods (Chen et al. 2021a):

1. we calculated the kinematic characteristics within $\sim 1{,}500$ pc and extend the applicable range of kinematic methods.

2. We also refit the AVR. Thanks to the enlargement of the sample and the improvement of the accuracy of data, the error of AVR coefficient is greatly reduced, and the kinematic age error decrease to $\sim 10\% - 20\%$.

Construct Kinematic catalogs

By combining data from Gaia, LAMOST, APOGEE, RAVE and NASA exoplanet archive, we construct the kinematic catalogs (e.g., Galactic position, velocity component membership) for 2,174 stars hosting 2872 planets.

Besides, in order to have a reliable Galactic census of planets (e.g., occurrence rate), one also needs accurate characterizations of the homogeneous filed stars. Here we focus on the Kepler targets because the Kepler mission has provided an unprecedented legacy sample for exoplanet science. By combining astrometry data from Gaia DR2 and radial velocity from LAMOST DR4 (with no bias to planet hosts), we present a LAMOST-Gaia-Kepler catalogue of 35,835 Kepler stars with kinematic properties and other basic parameters (Chen et al. 2021b).

radius valley

With the large planet sample provided by Kepler, statistical studies have revealed an important planetary feature, i.e., a radius valley (a paucity of planets around two Earth radii) that separates rocky, compact super-Earths and sub-Neptunes with lower bulk densities.

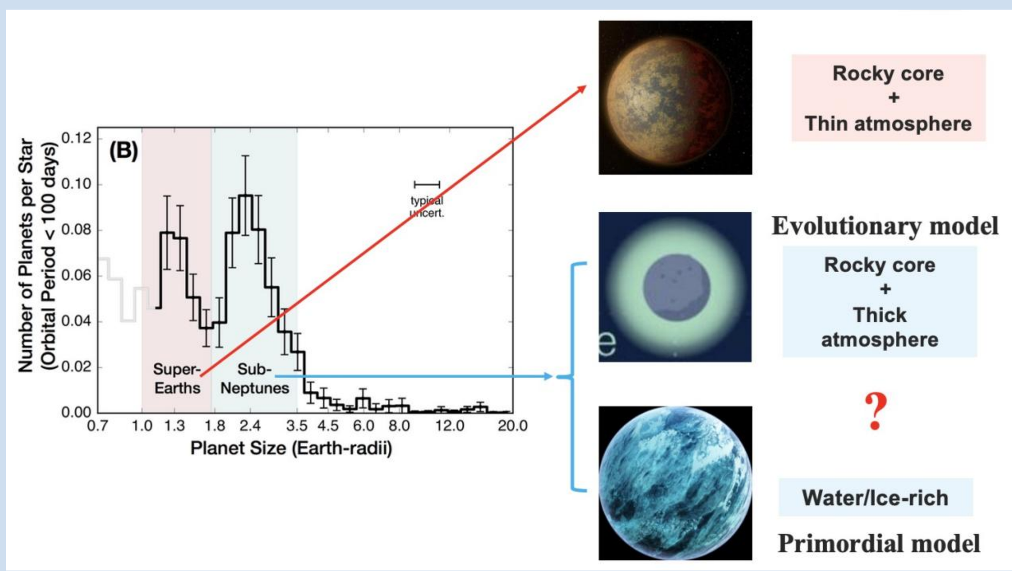

***Figure 2**: Radius valley and its mechanisms.*

Until now, various theoretical models have been proposed to explain radius valley, which can be generally divided into two categories: evolutionary models and primordial models. From the view of evolutionary models, sub Neptune is composed of a rocky core and a thick gas envelope. The envelope of some sub-Neptune is stripped, leaving only the rocky core, forming the observed radius valley. The energy source that drives the atmosphere loss process could be either from the radiation of host star (photo-evaporation mechanism), or the cooling luminosity of planet core (the core-powered mass-loss mechanism). From the view of primordial models, the radius valley is a natural result from planet formation and migration. Some studies suggested that the valley emerged because of the formation of two distinct planet populations with two different compositions, i.e., rocky super-Earth and water/ice-rich sub-Neptune.

Evolution trends of Radius valley

Based on the LAMOST-Gaia-Kepler catalog, we performs a systematical investigation into how the radius valley morphology varies with stellar age and metallicity by using the LAMOST-Gaia-Kepler catalog (Chen et al. 2022). After applying parameter control to isolate the effects of stellar age and metallicity, we then find a number of correlations, which are summarized as follows:

1. The average radius of Neptunes and sub-Neptunes ($R^{+}_{\rm valley}$) continuously decrease with age, supporting that (at least some) sub-Neptunes and Neptunes should be made with significant H/He envelope. While the average radii of planets below the radius valley (<1.7 Earth radii, $R^{-}_{\rm valley}$) show no significant dependence on age

2. The radius valley emerged before 1 Gyr and continued evolving on Gyr timescales, suggesting both photo-evaporation and core-powered mass loss make effects.

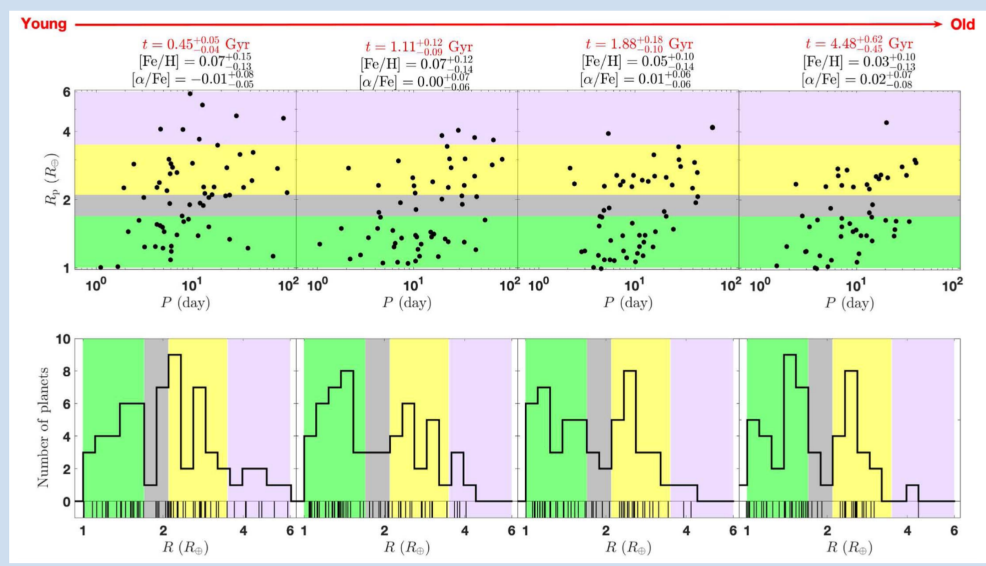

***Figure 3**: The period–radius diagram (top panel) and radius distribution (bottom panel) of planets with different kinematic ages t(Gyr).*

3. The number ratio of super-Earths to sub-Neptunes ($A_{\rm valley}$) monotonically decreases with [Fe/H] and [α/Fe]. That is to say, sub-Neptunes favor Fe-rich and alpha-rich stars, suggesting metallicities (not only Fe but also other metal elements, e.g., Mg, Si, Ca, Ti) play important roles in formation of sub-Neptunes.

References

[1] Chen et al. (2021a). PAST. I. Characterizing the Memberships of Galactic Components and Stellar Ages: Revisiting the Kinematic Methods and Applying to Planet Host Stars. ApJ 909, 115

[2] Chen et al. (2021b). PAST. II. Catalog and Analyses of the LAMOST-Gaia-Kepler Stellar Kinematic Properties. AJ 162, 100

[3] Chen et al. (2022). PAST. III. Morphology of the Planetary Radius Valley as a Function of Stellar Age and Metallicity in the Galactic Context Revealed by the LAMOST-Gaia-Kepler Sample. AJ 163, 249