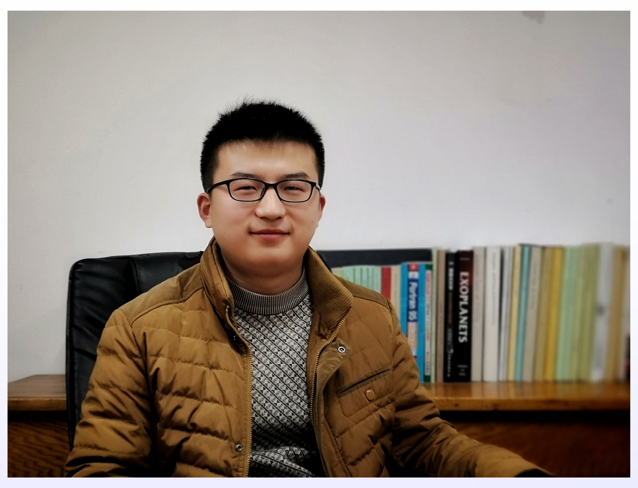
# The evolution of hot Jupiters revealed by the age distribution of their host stars



Di-Chang Chen[1], Ji-Wei Xie[1], Ji-Lin Zhou[1] and Subo Dong[2]

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*1. School of Astronomy and Space Science, Nanjing University, Nanjing, China.*
*2. Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, China.*
*email: dcchen@nju.edu.cn; jwxie@nju.edu.cn; zhoujl@nju.edu.cn; dongsubo@pku.edu.cn.*

## Abstract

**The unexpected discovery of hot Jupiters challenged the classical theory of planet formation inspired by our solar system. Until now, the origin and evolution of hot Jupiters are still uncertain. Determining their age distribution and temporal evolution can provide more clues into the mechanism of their formation and subsequent evolution. Using a sample of giant planets around Sun-like stars collected from the kinematic catalogs of the Planets Across Space and Time project, we find that hot Jupiters are preferentially hosted by relatively younger stars in the Galactic thin disk. We subsequently find that the frequency of hot Jupiters declines with age. In contrast, the frequency of warm/cold Jupiters shows no significant dependence on age. Such a trend is expected from the tidal evolution of hot Jupiters' orbits, and our result offers supporting evidence using a large sample. We also perform a joint analysis on the planet frequencies in the stellar agemetallicity plane. The result suggests that the frequencies of hot Jupiters and warm/cold Jupiters, after removing the age dependence are both correlated with stellar metallicities. Moreover, our derived relations can help explain the long-standing discrepancy between hot Jupiter frequencies from RV and transit surveys and the null detection of hot Jupiters in old globular clusters.**

## Introduction

Hot Jupiters generally refer to Jupiter-size planets with orbital periods $\lesssim 10$ days around host stars. Since the discovery of the prototype 51 Pegasi b in 1995, hot Jupiters have been one of the most studied exoplanet populations because The existence of Jovian planets on such short periods poses significant challenges to the classical planet formation theories based on our solar system.

It is now known that the most hot Jupiters are formed beyond the ice-line and then migrate inward via the interaction of planetary disk (the disk migration mechanism) and/or the perturbation by by outer binaries or companions (the high-eccentricity migration mechanism). To test these models, lots of studies have explored the properties of hot Jupiters and their correlations with the host stars. However, the origin of hot Jupiters remains puzzling.

An understudied but crucial probe into the formation and evolution history of hot Jupiters is their dependence on the hosts' ages:

**(1). Are there any differences in the hosts' age distributions between hot Jupiters and warm/cold Jupiters?**

**(2). Does the frequency of hot Jupiters evolve with age? And if so, how?**

The answers to these questions can constrain their origin and evolution, especially revealing whether/how the tidal interactions with host stars shape their orbits.

## Method and sample

The main bottleneck of investigating the temporal evolution of hot Jupiters has been the difficulty of making decent age estimates for the hosts. In the recent year, thanks to the high-quality astrometry and radial velocity data, the average age of an assemble of stars can be estimated from their kinematics using the age-velocity dispersion relation (AVR). In the Planet Across Space and Time (PAST) series, we have refined the AVR to derive the kinematic ages with inner uncertainties of $10\% - 20\%$ and constructed catalogs of stellar kinematic properties. Based on the kinematic catalogs, we select 383 giant planets around single Sun-like stars in the Galactic disks. In specific, our planetary sample consists of 29 hot Jupiters and 40 warm/cold Jupiters detected by space-based facilities with transit method (ST), 147 hot Jupiters, and 3 warm/cold Jupiters detected by ground-based facilities with transit method (GT), 17 hot Jupiters and 147 warm/cold Jupiters detected with radial velocity method (RV).

## Age distributions

We calculate the average kinematic ages from the vertical velocity dispersions of hot Jupiter and warm Jupiter hosts with the refined AVR. The resulting average ages are $3.24^{+0.43}_{-0.32}$ Gyr and $5.21^{+0.68}_{-0.60}$ Gyr for the hot Jupiter hosts and warm/cold Jupiter hosts, respectively (see the solid points in Fig. 1). Hot Jupiter hosts are $1.97^{+0.75}_{-0.72}$ Gyr younger than warm/cold Jupiter hosts by a confidence level of 99.72% considering the data uncertainties.

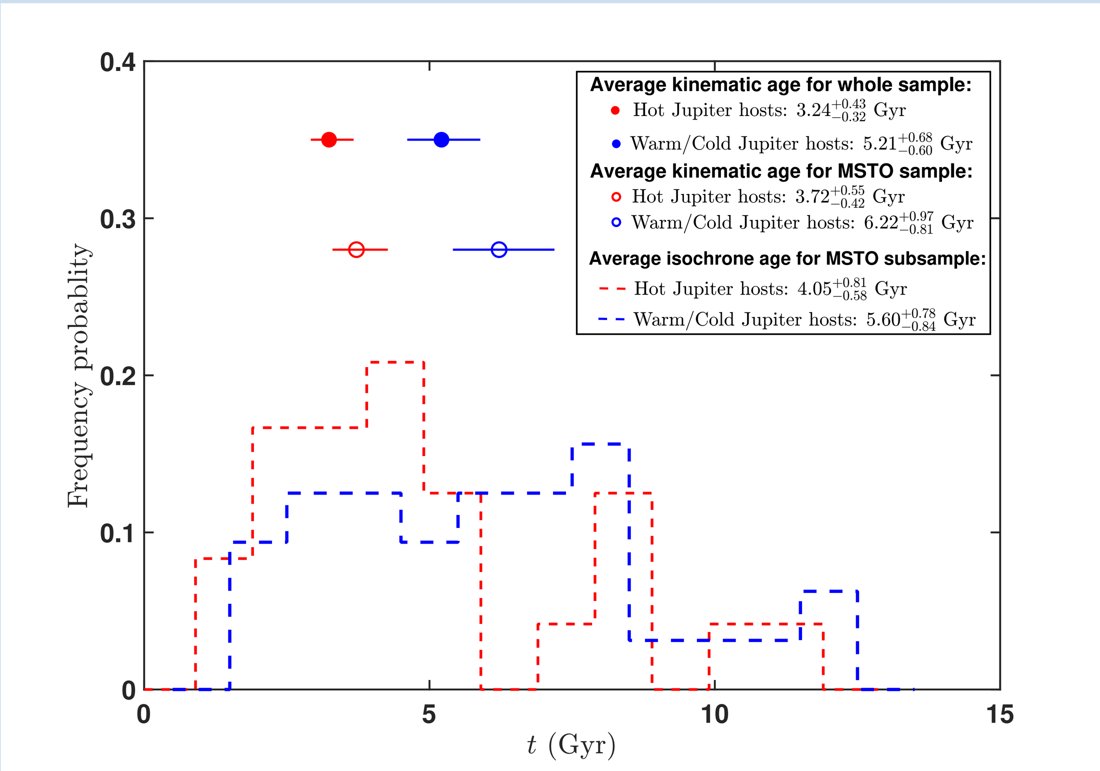


***Figure 1**: The average kinematic ages for the hot Jupiter hosts (solid red point) and warm Jupiter hosts (solid blue line point). For comparisons, the distributions of isochrone ages for the main-sequence turn-off (MSTO) subsamples are plotted as dashed histograms.*

To further verify the above result, we also consider a subsample of MSTO stars having relatively well-determined individual ages with a typical uncertainty of $\sim 20\% - 30\%$. As shown as dashed lines in Fig. 1, for the MSTO subsample, hot Jupiter hosts generally have younger isochrone ages (average as ($4.05^{+0.81}_{-0.56}$ Gyr) compared to warm/cold Jupiter hosts (average as $5.60^{+0.78}_{-0.84}$ Gyr) by $\sim 1.55$ Gyr, which is consistent with the kinematic results.

## Temporal evolution

We further correct the detection biases and explore the temporal evolution of the frequencies (i.e., the intrinsic fractions of stars hosting planets) of hot Jupiters and warm/cold Jupiters. Specifically, we construct the parent stellar samples for the three subsamples (RV/GT/ST) by using data from the Lick/HIRES/Keck/HAPRS RV database, Tycho-2/SuperWASP, and Kepler, respectively. Then we obtain the frequencies of hot Jupiters $F_{\rm HJ}$ and warm/cold Jupiters $F_{\rm WJ/CJ}$ of different age by correcting the geometric effect and detection efficiency.

## Temporal evolution

The kinematic age is known to be correlated with other stellar properties such as mass and metallicities. Since we only study Sun-like hosts, the stellar masses in different age bins do not differ significantly, while the stellar metallicities decrease with increasing age. To qualify the dependence of $F_{\rm HJ}$ and $F_{\rm WJ/CJ}$ on stellar age/[Fe/H], we perform the Bayesian analysis for each of the three subsamples. The best fits are:

$$F_{\rm HJ} \propto 10^{(1.6^{+0.3}_{-0.3} \times [{\rm Fe/H}])} \times \exp(-0.20^{+0.06}_{-0.06} \times \frac{t}{\rm Gyr}), \quad [1]$$

$$F_{\rm WJ/CJ} \propto 10^{(1.1^{+0.2}_{-0.3} \times [{\rm Fe/H}])} \times \exp(0.02^{+0.02}_{-0.03} \times \frac{t}{\rm Gyr}). \quad [2]$$

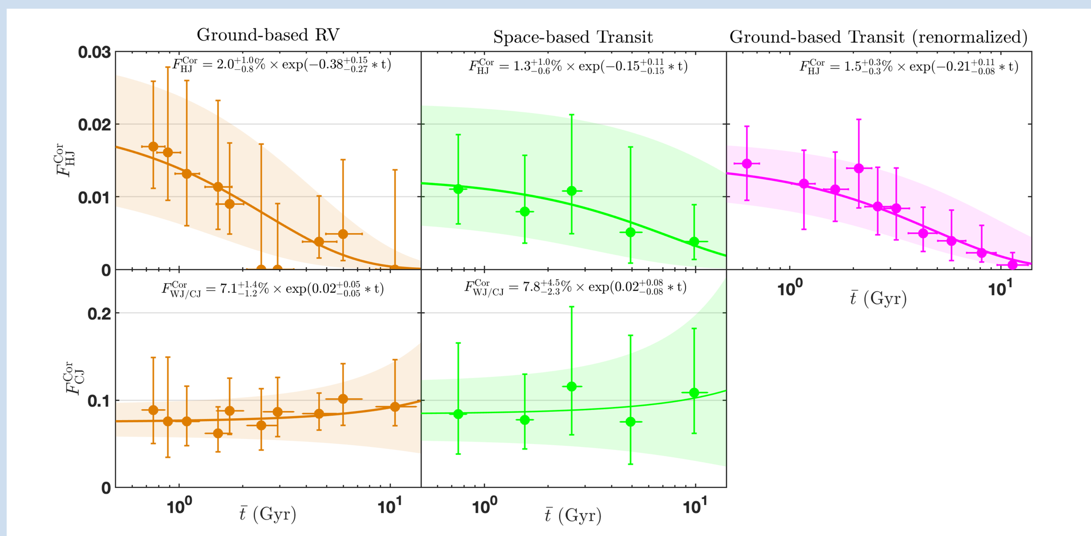


***Figure 2**: The frequencies of hot Jupiters (Top panels) and warm/cold Jupiters (Bottom panels) as functions of average kinematic age for the RV, ST (Middle), and GT (Right), after normalizing the frequencies to solar metallicity.*

Fig. 2 shows the metallicity-'corrected' frequencies after normalizing to the solar metallicity. As can be seen, as kinematic age increases, for all the three subsamples, the frequencies of hot Jupiters decline at confidence levels of $\gtrsim 2 - 3\sigma$. In comparison, warm/cold Jupiter frequencies have no significant dependence on age.

## Implication

The age-frequency trends are expected from tidal decays of hot Jupiters' orbits, offering large-sample supporting evidences. Our results also imply that the bulk of hot Jupiters may arrive relatively early since the birth of their hosts because otherwise, the late-arrived hot Jupiter can lead to increases in frequency.

Moreover, the above correlations can help explain why the hot Jupiter frequencies inferred from radial velocity surveys are higher than those derived from transit surveys, given that RV targets tend to be more metal-rich ($\sim 0.06$ dex) and younger ($\sim 1$ Gyr) than transits. Our results also help explain the null detection of hot Jupiters in the globular cluster 47 Tucanae by further considering the effect of age on $F_{\rm HJ}$.