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Statistical Signature and Its Theoretical Implication in Hot Jupiter Population

S. Mondal *

Department of Physics, Bidhannagar College, EB-2, Salt Lake, West Bengal, 700064, India

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Abstract

Hot Jupiters, a special class of exoplanets, always draw attention due to their intriguing characteristics. In this paper, we have continued our endeavor to understand the distribution of hot Jupiter populations and the architecture of planetary systems through the statistical framework. Different techniques to discover hot Jupiters have been studied here, and current data suggested that the transit method has better chances of discovering light and short-period candidates. Relation between orbital eccentricity and other planetary parameters like mass and orbital periods have been investigated to support the existence of a discontinuity in planetary mass distribution at ~4 M_J. A low *p*-value in the KS test indicates the existence of two different populations of hot Jupiters having a possibly different channel of formation. We also discussed these statistical results' theoretical and empirical implications for dynamical evolution.

Keywords: Exoplanet; Hot Jupiter; Orbital eccentricity; Planetary migration.

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1. Introduction

An extra dimension has been appended to our space knowledge with the discovery of extra solarolar planets in the early nineties [1,2]. Exoplanet research is one of the most rapidly developing subjects in present astronomy [3]. From countless stars around us, few have giant planets in their close proximity. The high temperatures of the protoplanetary disc and low orbital period of those planets, namely hot Jupiters (HJs), make them prime candidates for *in situ* planetary formation research. In recent times, substantial efforts have been dedicated to characterizing a bunch of planetary parameters of hot Jupiter through different observational methods [4]. Those detailed studies involving mass, metallicity, orbital characteristics, etc., help us to disentangle the intricate hot Jupiter population [5].

2. Parametric Influence on Discovery Techniques

Most of these exoplanets have been detected through planetary transit or radial velocity studies of the host star [6]. Due to the large gravitational tug by host stars, their signature

* *Corresponding author*: soumyabrata_mondal@yahoo.in

in the Doppler method of planet search is very strong [7]. But this technique is biased towards finding hot Jupiters around less massive stars. Again, wide-angle CCD cameras monitoring light from tens of thousands of stars are finding hot Jupiter transits much faster than the Doppler wobble method [8]. A precise combination of both techniques can lead us to new achievements [9]. Apart from them, few have been discovered by imagining or through planet-lens signatures detected during gravitational lensing events [10], but the population in this category is low as it is suitable for planets residing at large separations from their host star. A small population of giant HJs, closely orbiting its host star, has been discovered through the pulsar method [11].

Ever-enriching exoplanet catalogs [12,13] unleash the potential for statistical studies. Our observation based on available data from those catalogs predicts that the transit method has a better chance of discovering lightweight hot Jupiters with lower eccentric orbital (Fig. 1). Lower orbital inclinations increase the possibility of capturing dimness of starlight by parallel monitored wide-angle CCD lenses during their transits in front of its parent star [14]. Distributions of different discovery techniques in the period-mass diagram (Fig. 2) also show that low-mass and short-period hot Jupiters are frequently discovered through transit. Though both Figs. 1 and 2 are not free from observational bias and instrumental limitation. However, they are keeping some valuable information about the process of formation and migration of those detected hot Jupiters. In particular, a cluster of HJs can be observed with a mass of less than 4 M_J. These low-mass planets have a full range of eccentricities with an average eccentricity value. Beyond it, a lack of lower eccentric HJs can be observed up to 8 M_J. This relative paucity of HJs with intermediate mass can be related to disk migration [15] and can be referred to as a mini "period valley" [16]. An average eccentricity of $0.05_0^{0.5} \pm 0.008$ for intermediate and large hot Jupiters indicates a lack of influence of tidal interaction on larger mass. Previous study shows a highly eccentric giant planet usually eject water-rich material from the planetary system [17] rather than scattering inward [18] and circulating its orbit, which results in fewer low eccentric giant hot Jupiter populations [19,20]. A large catalog of hot Jupiters will also help to establish how their abundance, mass, orbital period, and eccentricity depend on the host star or disk environment.

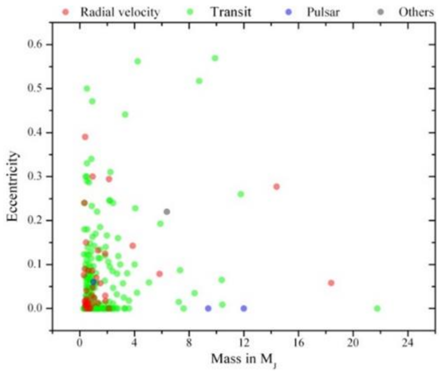

Fig. 1. Planet mass vs. orbital eccentricity plot specifying their discovery history. A discontinuity in population can be observed around 4 $M_{J.}$

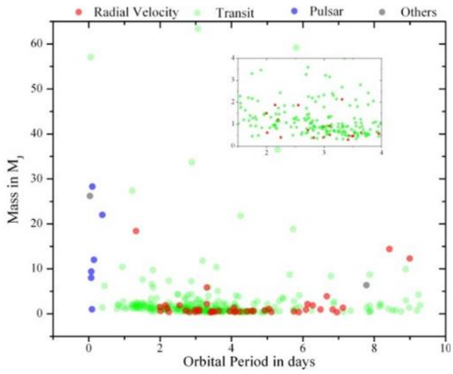

Fig. 2. Plot between planetary mass and orbital period is observed here for different discovery techniques. Inset displays distribution of lightweight population elaborately.

3. Data and Analysis

Several well-known agencies compiled literature-based exoplanet catalogs to provide a comprehensive tool for statistical studies. These catalogs include well-accepted information about the different physical properties of the planets, as well as their parent stars. Different agencies use different criteria to include exoplanets in their catalog, and their technical methods to calculate planetary parameters also differ. After scrutiny, we have shortlisted more than 300 common hot Jupiters for our analysis from those databases.

An elaborate report on the formation of hot Jupiters and its dependency on host star metallicity has already been published [21]. It also threw a hint at the presence of different groups in the hot Jupiter family through size and density correlation. To continue the legacy here, we have illustrated a few other planetary parameters to foster further connection between them.

3.1. *Formation and migration depending on metallicity*

Inflated size and close proximity to the host star of hot Jupiters indicate *in situ* formation. We have already argued about the rapid formation of the gaseous atmosphere around its rocky core before the protoplanetary disk dissipates [21]. A drive of hot Jupiters is a complex model parameterized by several planetary arguments. For single-child hot Jupiters, the migration speed to their current orbit largely depends on parental metallicity. The existence of gas giants evolved through the core accretion model is highly correlated to disk metallicity, and it was elaborately discussed in an early report. In the case of multiple planetary systems, any planetary scattering that occurs due to perturbation creates a field for the tidal circularisation model. Here, an excitation in eccentricity due to any secular perturbation follows by migration [22].

3. 2. *Eccentricity distribution*

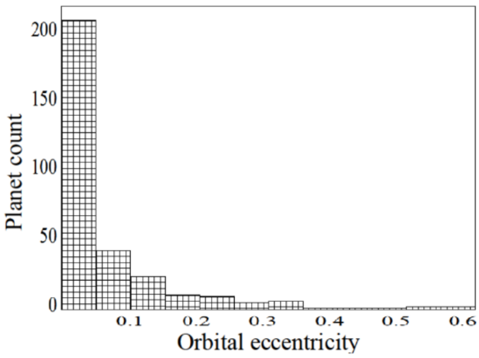

Fig. 3. Orbital eccentricity distribution with mean $<\varepsilon>$0.03 and standard deviation σ 0.1.

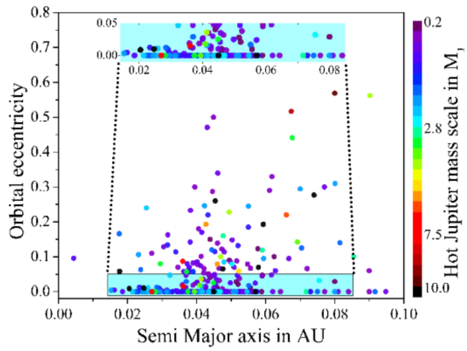

Fig. 4. Distribution of orbital eccentricity as a function of semi major axis for hot Jupiters. Here we have considered hot Jupiters with mass up to 10 M_J. Different colours represent planetary mass in M_J unit.

Orbital eccentricities as influencing parameters in planetary migration are also observed for better understanding. Apparently, most of the hot Jupiters prefer circular or near-circular orbit (Fig. 3), whereas spread in eccentricity observed as the planet goes far from its host star (Fig. 4). Hot Jupiters having semi-major axis greater than 0.04 AU are less influenced by host star and more eccentric than closer ones, even massive hot Jupiters close to parent star are trying to circularize their orbit under the influence of tidal effect. Higher eccentricity for massive HJs with greater semi-major axis indicates their inward migration. Eccentricity excitation and tidal circularization due to low orbital period make hot Jupiters stay in close proximity (Fig. 5). Their nonvoid eccentricity can be referred to as either a continuous attempt to drive them out from circular orbit or they have migrated inwards from a greater orbit were eccentricity generally high. The probability of the first option decays with the increasing mass of planets due to their greater inertial resistance. Lightweight hot Jupiters may easily get into resonance traps and be tied under circular orbit. Though there are few "free-spirited" lightweight, hot Jupiters are still having high orbital eccentricity. They mostly come from a single planetary system and propagate through disk migration.

The large eccentricities required to initiate circularization could be generated differently. Time-dependent stellar flux influences the eccentric hot Jupiter's atmospheric dynamical regime, affecting orbital motion [23]. For lighter planets, tidal interaction with the parental disk is reduced significantly to initiate eccentric growth (Fig. 6). Generally, planet-planet scattering for multiple planetary systems or orbital perturbation due to close encounters by massive objects can initiate eccentricity excitation [24]. So, it can be assumed that a fraction of massive ones are formed at a large distance from the host star and as they migrate towards the host star due to either the chaotic interactions of a multi-planetary system or the long-term perturbation of a highly inclined system, which lead to the innermost giant planet passing close enough to the host star that tidal interactions strip its angular momentum and circularize its orbit. Difficulty in circularizing planets by host star is proportional to planetary mass and function of orbital speed. To provide a consolidated view, we need more data in the hot Jupiter catalog, which incidentally is on the way due to phenomenal progress in exoplanet research nowadays.

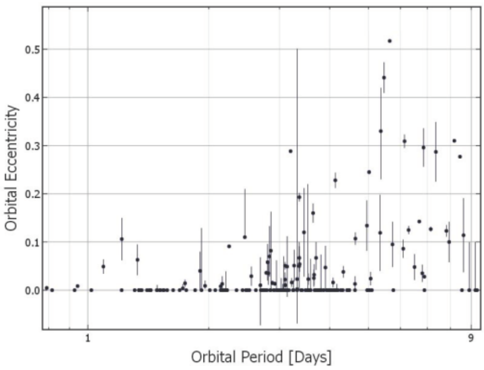

Fig. 5. Dependency of orbital eccentricity with the orbital period.

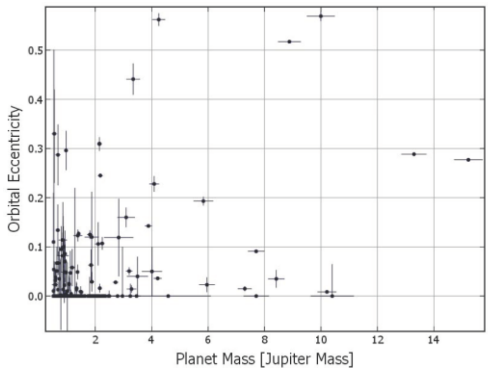

Fig. 6. Dependency of orbital eccentricity with the planetary mass.

3.3. *Mass distribution*

Our analysis of different orbital and physical parameters shows that the hot Jupiter population can be divided into two groups. The lightweight group has a mass less than four times Jupiter's mass, and the heavyweight group has the rest of the population. To check the nature of eccentricity distribution, we have performed a probability plot on each group (Fig. 7). Blom scoring method was employed to mark and check their difference from the normal distribution reference line. All the different parametric distributions carried individual distinguishable remarks. As most of the close-orbiting HJs have been circularized, their orbit eccentricity is not normally distributed for both groups. In fact, the Heavyweight group is far more aligned to the reference line. This shows randomness in eccentricity for heavier hot Jupiters. Lightweight planets with close orbital paths to their host star easily fall into resonance perturbation and circularize their orbit.

To verify our hypothesis in more detail, we compare those two mass regimes' planetary orbital eccentricity distributions. We have employed a two-sample Kolmogorov–Smirnov test for the statistical analysis. It shows two distributions have a *p*-value of 0.037 (STD=0.1). It is very low, suggesting a significant difference between the two mass regimes.

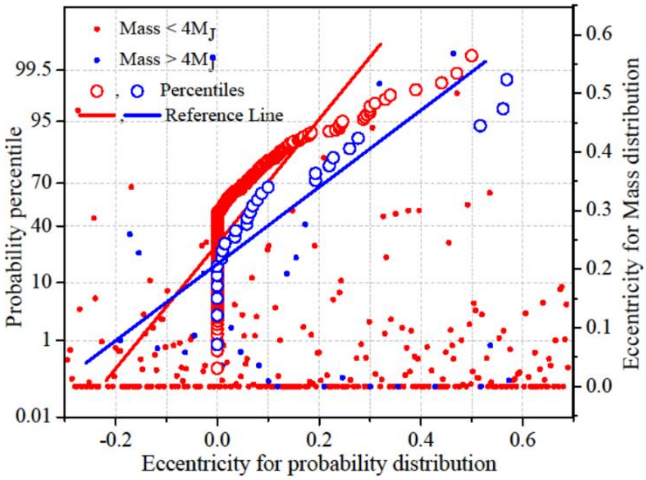

Fig. 7. Orbital eccentricity distribution for two groups of hot Jupiters. Red and blue colors describe HJs having mass less and greater than $4M_J$. Their probability of normal distribution is also sketched with a reference line to indicate the presence of different populations.

4. Conclusion

Significant progress made in the search for exoplanets in the last few years has produced an opportunity to look at them from different perspectives. Different astronomical methods (especially transit- and radial velocity-based) have been employed to discover exoplanets. Here, we have investigated the properties of those methods using the statistical framework. Overlooking rudimentary differences in those detecting methods, it has been established that low-mass and short-period hot Jupiters are frequently discovered through the transit method, and as the transit method takes the front seat in current space search missions so in coming days, the population of less dense hot Jupiters is going to be denser.

A detailed study of orbital eccentricities and their correlation with other orbital and planetary parameters has been performed here. It has been observed that Hot Jupiters very close to the parent star (<0.04 AU) are more eccentric; even massive hot Jupiters are trying to circularize their orbit under the influence of tidal effect. Most of the hot Jupiters prefer low orbital eccentricity, and it carries their migration signature. Higher eccentricity for massive HJs with greater semi-major axis indicates their inward migration. Results presented above suggested hot Jupiters having masses above and below ~$4M_J$ coming from two different populations. The presence of two different groups in mass distribution is supported by a low *p*-value in Kolmogorov–Smirnov test. Available cross-discipline references lack the robustness to expand these models for single and multiplanet systems. All these interesting characteristics make hot Jupiters a prime target for cultivation.

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