INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

Observational Evidence of Bimodal Distribution in Hot Jupiter Population

Soumyabrata Mondal[1]*

1 Department of Physics, Bidhannagar College, Salt Lake, 700064, West Bengal, India

OPEN ACCESS

Received: 11-08-2023

Accepted: 13-09-2023

Published: 27-10-2023

Citation: Mondal S (2023) Observational Evidence of Bimodal Distribution in Hot Jupiter Population. Indian Journal of Science and Technology 16(40): 3471-3478. https://doi.org/10.17485/IJST/v16i40.2045

* **Corresponding author**.

soumyabrata_mondal@yahoo.in

Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Abstract

Objectives: Hot Jupiters, a special class of exoplanets always draw attention due to their intriguing characteristics. Here we wish to establish the differentiation of two planetary mass groups having orbital eccentricity discrimination. **Methods**: A comprehensive statistical approach has been carried out to understand the distribution of hot Jupiter population and the architecture of those planetary. 312 hot Jupiters have been filtered out from 4285 different scientifically recognized exoplanet databases and such a huge hot Jupiter sample size has not been used to find out any intrinsic correlation before. Different techniques to discover hot Jupiters have been studied here to segregate them. Relation between orbital eccentricity and other planetary parameters like mass, orbital periods have been investigated further to find any intrinsic characteristics. **Findings**: We established that transit method has better chances to discover light and short period candidates. Their orbital eccentricity has been studied w.r.t. their calculated planetary mass and orbital period. We have found eccentricity excitation and tidal circularisation due to low orbital period keeps hot Jupiters at close proximity to their parent stars. Effectively smaller average eccentricity of $0.05_0^{0.5} \pm 0.008$ for intermediate and large hot Jupiters indicates lack of influence of tidal interaction on larger masses. Probability distribution of eccentricity supports the existence of a discontinuity in planetary mass distribution at ~4M_J. Low p value (~0.037) in KS test indicates the existence of bimodal distribution of hot Jupiter populations having possibly different channel of formation. **Novelty:** Application of statistics on hot Jupiters is rare due to their infrequent detection. Already reported planetary parametric features of exoplanets are checked for trueness and new parameters have been studied. Here we also discussed theoretical and empirical implications of these statistical results for dynamical evolution. It opens up a new dimension to scientific realm.

Keywords: Hot Jupiter; Exoplanet; Mass distribution; Eccentricity; Transit method; Bimodal distribution

1 Introduction

An extra dimension has been appended to our space knowledge with discovery of extra-solar planets in early nineties [1,2]. Exoplanet research is one of the most rapidly developing subjects in present astronomy[3,4]. Despite having a large sample size in exoplanet catalogue, there are very few attempts have been made to characterize them with help of statistical methods[3,5]. Construction of such cross-platform bridge has been attempted here. From countless stars around us few are having 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 time substantial efforts have been dedicated to characterise a bunch of planetary parameters of hot Jupiter through different observational methods[6,7]. Current exoplanet discovery trend is piling up hot Jupiter numbers to make them suitable for applying statistical techniques to other planetary parameters. Origin of hot Jupiter is still a speculation; disk migration and high eccentricity migration are two recognized individual models for their formation and migration[8]. Initial findings suggest existence of different hot Jupiter populations but no concluding evidence has been delivered yet[4,9]. Furthermore, a recent observation portraying dependency of mass distribution on orbital period proposed *in situ* formation model and predicted a correlation of giant planet migration to its orbital shape[10]. It intrigues us to forward the study further to find any intrinsic feature hidden in their orbital eccentricity distribution. Recent thermal emission observations of several hot Jupiters provide us opportunity to look into their compositional diversity but due to lack of available data they cannot be grouped. Till more and more hot Jupiters come under the surveillance this direct observational deficiency can be overcome through studying other available parameters. Those detailed studies involving mass, metallicity, orbital characteristics etc. help us to disentangle the intricate hot Jupiter population[11]. In this paper we have tried to guide the exploration to accelerate the discovery rate of hot Jupiter and, also checked the correctness of different existing hypothesis related to exoplanet paternity.

2 Methodology

2.1 Parametric influence on discovery techniques

Most of these exoplanets have been detected through planetary transit or radial velocity studies of the host star[3,12]. Due to large gravitational tug by host stars, their signature in the Doppler method of planet search is very strong[13]. 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[14]. A precise combination of both the techniques can lead us to new achievement[15]. Apart from them, few have been discovered by imagining or through planet-lens signatures detected during gravitational lensing events[16], but population in this category are low as it is suitable for planets reside at large separations from their host star. A small population of giant HJs, closely orbiting its host star has been discovered through pulsar method[17].

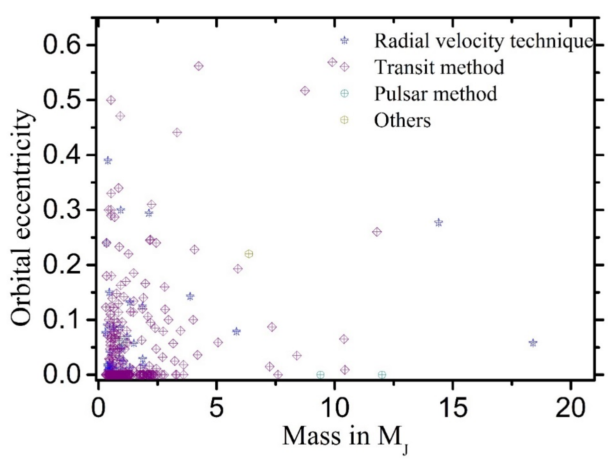

Fig 1. A scattered diagram to demonstrate the distribution of orbital eccentricities over hot Jupiter masses, specifying their discovery history

Ever enriching exoplanet catalogues[18,19] unleashes the potential for statistical studies. Our observation based on available data from those catalogues predicts transit method has better chances to discover lightweight hot Jupiters with lower eccentric orbital (Figure 1). Lower orbital inclinations increase the possibility of capturing dimness of starlight by parallel monitored

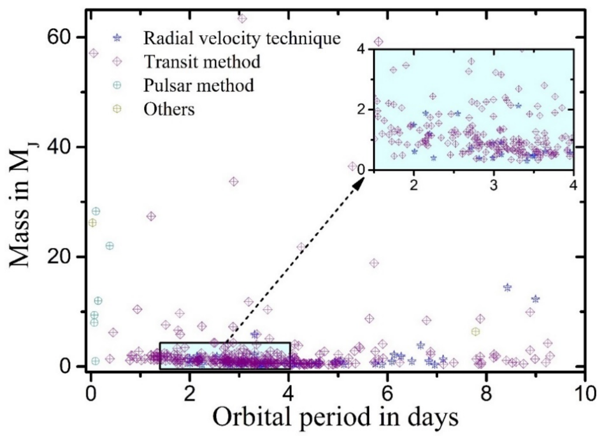

Fig 2. A scattered diagram to demonstrate the distribution of hot Jupiter masses over their orbital periods for different discovery techniques. Inset displays distribution of lightweight population intricately

wide angle lenses during their transits in front of its parent star [20]. Distributions of different discovery techniques in period-mass diagram (Figure 2) also shows low-mass and short-period hot Jupiters are frequently discovered through transit method. Hence, with different ongoing and upcoming space missions looking for starlight from never explored corners of universe has opened the opportunity to discover smaller hot Jupiters closest to their parent star. Though both Figures 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 mass less than 4 M_J. These low mass planets have a full range of eccentricities with average value of eccentricity. Beyond it lack of lower eccentric HJs can be observed upto 8 M_J. This relative paucity of HJs with intermediate mass can be related to disk migration [9], and can be referred as mini "period valley" [21]. An average eccentricity of $0.05_{0}^{0.5} \pm 0.008$ for intermediate and large hot Jupiters indicates lack of influence of tidal interaction on larger masses. Previous study shows a highly eccentric giant planet usually eject water-rich material from the planetary system rather than scattering inward [22,23] and circulating its orbit, which results in fewer low eccentric giant hot Jupiters population [24]. We present the evidence of this theory later in eccentricity distribution analysis. In coming days, a larger catalogue of hot Jupiters will also help to establish how their abundance, mass, orbital period and eccentricity depend on host star or disk environment.

3 Results and Discussion

3.1 Formation and migration depending on metallicity

Inflated size and close proximity to host star of hot Jupiters indicate *in situ* formation. We have already argued about rapid formation of gaseous atmosphere around its rocky core before protoplanetary disk dissipates [25]. Drive of hot Jupiters is a complex model parameterised by several planetary arguments. For single child hot Jupiters, the migration speed to their current orbit largely depends on parental metallicity. Existence of gas giants evolved through core accretion model is highly correlated to disk metallicity and, it was elaborately discussed in our early report [25]. In case of multiple planetary system, any type of planetary scattering occurred due to perturbation create a field for tidal circularisation model. Here an excitation in eccentricity due to any secular perturbation follows by migration [26]. A recent study on host star metallicity of HJs suggested population of HJs formed in a similar process to other gas giants, and may differ only in their migration histories [27]. When we have dug it further with a larger set of samples, no conclusive evidence has been inferred as already reported [28]. It motivated us to cultivate other planetary parameters viz. eccentricity or mass for any multimodal distribution.

3.2 Eccentricity distribution

Orbital eccentricities as influencing parameter in planetary migration draws attention to scientific community in recent times and, high-eccentric migration models have been proposed based on misalignment between the stellar spin and orbital angular momentum axes [29,30]. Here we have revisited that hypothesis from their present scenario. Orbital eccentricity distribution

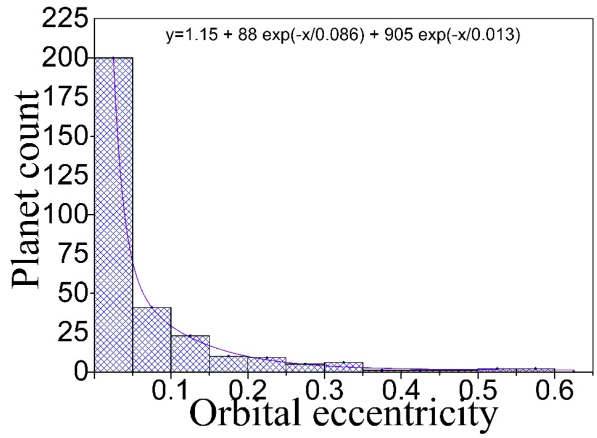

Fig 3. Orbital eccentricity distribution with mean 0.058 and standard deviation 0.1. It is well fitted by exponential decay curve as described in figure

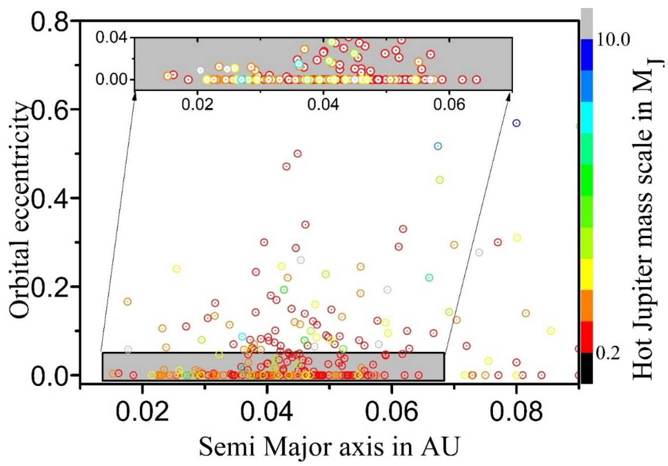

Fig 4. A representation of orbital eccentricity as a function of semi major axis for hot Jupiters. Here we have considered hot Jupiters with planetary mass up to 10 M_J. Colour map represents planetary mass in M_J unit

exhibits, most of the hot Jupiters prefer circular or near circular orbits, irrespective of their sizes (Figure 3). Whereas divergence in eccentricity has been observed as planet goes far from its host star (Figure 4). Our study confirms HJs having semi major axis greater than 0.04 AU are less influenced by host star and more eccentric than closer ones, even massive HJs close to parent star are trying to circularize their orbit under influence of tidal effect. It supports recent report on tidal disruption and accretion of remnant planetary bodies theory around white dwarf[(31)]. Hence, we can propose a bridge between close hot Jupiters and circumstellar debris disks in the proximity of the white dwarf to exchange planetary formation theory. Higher eccentricity for massive HJs having greater semi major axis indicates their inward migration. Eccentricity excitation and tidal circularization due to low orbital period makes hot Jupiters to stay at close proximity (Figure 5). Their non-void eccentricity can be referred as either by continuous attempt to drive them out from circular orbit, or they have migrated inwards from a greater orbit where eccentricity generally high. Probability of first option decays with increasing mass of planets due to their greater inertial resistance. Lightweight hot Jupiters may get into resonance trap and tied under circular orbit easily, though there is few “free spirited” lightweight hot Jupiters still having high orbital eccentricity. They are mostly coming from single planetary system and propagating through disk migration. A recent study only on transiting small planets also confirms single child planets are more eccentric than multi-planet system[(32)].

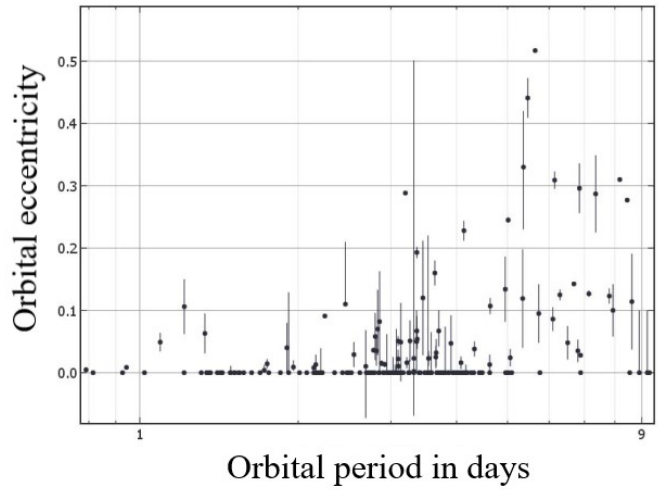

Fig 5. Dependency of orbital eccentricity with the orbital period. Only eccentricity uncertainties according to published data have been shown here

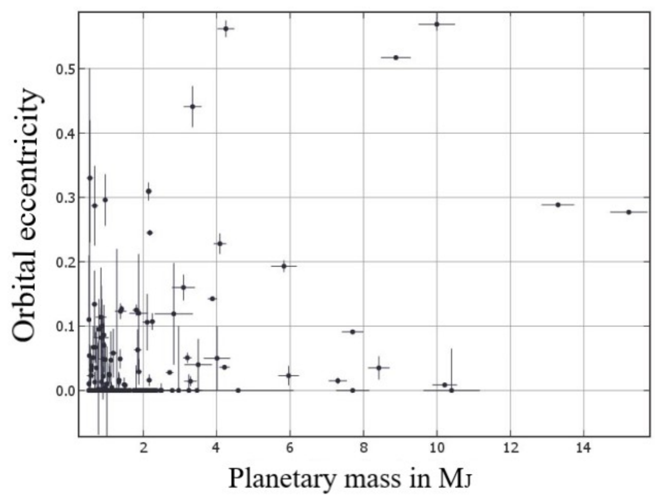

Fig 6. Dependency of orbital eccentricity with the planetary mass. Error bars indicates theoretical measurement uncertainties according to different repute reports

The large eccentricities required to initiate circularization could be generated in a different way. Time dependent stellar flux influences the eccentric hot Jupiter's atmospheric dynamical regime, which in turn affect orbital motion[(33)]. For lighter planets tidal interaction with the parental disk is reduced significantly to initiate eccentric growth (Figure 6). Generally, planet-planet scattering for multiple planetary system or orbital perturbation due to close encounter by massive objects can initiate eccentricity excitation[(34)]. So, it can be assumed that a fraction of massive ones is formed at large distance from host star and, as they migrated towards host star due either the chaotic interactions of a multi-planetary system or the long-term perturbation of 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 to circularize planets by host star is proportional to planetary mass and function of orbital speed. To provide a consolidated view we need more data in hot Jupiter catalogue which incidentally is on the way due to phenomenal progress in exoplanets research now days.

3.3 Mass distribution

Previous studies suggested that the mass distribution (exclusively on lighter HJs) may have two different maxima, separated by a valley[35]. As per our analysis over different orbital and physical parameters, hot Jupiter population can be divided over two mass regimes. Lightweight group having mass less than four times of Jupiter mass and, heavyweight group having rest of the population. Proposed bimodal population has been assessed through different statistical techniques applied on planetary parameters. To check the nature of distribution of orbital period and eccentricity of different hot Jupiters, we have performed probability plot on each group (Figure 7). Blom scoring method was employed to mark and check their difference from normal distribution reference line. All the different parametric distribution carried individual distinguishable remark. Analysis on orbital periods does not conclude any significance on differentiability between two groups. Both of them are very much aligned to their reference lines. Non-significant result arises because of our targeted small subgroup of hot Jupiters. If we remove our constrain regarding hot Jupiter attributes and widen spectrum of orbital periods for whole exoplanet catalogue, a demarcation could be obtained. It is beyond scope of this article. As most of the close orbiting HJs have been circularized their orbit so eccentricity is not normally distributed for both the groups. In fact, Heavyweight group is far more aligned to reference line. This shows randomness in eccentricity for heavier hot Jupiters. Lightweight planets having close orbital path to its host star easily fall in resonance perturbation and circularize its orbit.

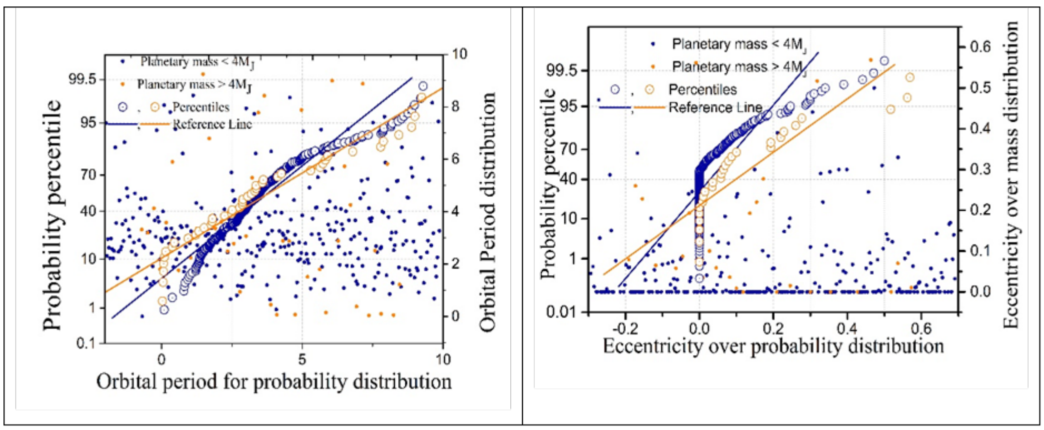

Fig 7. Different planetary parametric distributions for two groups of hot Jupiters. Left hand side exhibits orbital period and right side shows eccentricity variations. Blue and orange colours describe HJs having mass less and greater than 4M$_J$. Their probability of normal distribution is also sketched with reference line to indicate presence of different populations

To verify our hypothesis in more detail, we have compared the planetary orbital eccentricity distributions of those two mass regimes. We have employed 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 in two different mass regimes.

4 Conclusion

Significant progress made in search for exoplanets in last few years has produced an opportunity to look at them in different perspectives. Till date different astronomical methods have been employed to discover exoplanets. Here we have investigated properties of those methods using 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 transit method. As automated transit search programme is currently occupying major parts of space search missions, so in coming days, population of less dense hot Jupiters are going to be much heavier. It opens the possibility to study the properties of newly found HJs and, it will certainly help researchers to conclude the formation and migration models predicted in several earlier reports.

As hot Jupiters is a small subgroup of exoplanet community and, many studies has been already performed on different reported planetary parameters of several exoplanets, it inspired us to conduct similar tests on HJs. In this context, a detailed analysis on orbital eccentricities and, its correlation with other orbital and planetary parameters has been performed here. It has been observed that Hot Jupiters very close to parent star (<0.04 AU) are more eccentric, even massive hot Jupiters are trying to circularize their orbit under 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. Result presented above suggested hot Jupiters having masses above and below ~4M_J is coming from two different populations. Presence of two different groups in mass distribution is supported by low p value in Kolmogorov–Smirnov test. The inference is aligned to the nature of mass distribution of previously predicted exoplanet groups. Available cross-discipline references lack robustness to expand these models for single and multiplanet systems. Here we have opened up the realm of opportunity to endeavour the interdisciplinary research but further studies in near future, with larger sample size is required to pose more constrains on those models.

5 Acknowledgement

The Author is thankful to different exoplanets databases like The Extrasolar Planets Encyclopaedia, NASA exoplanets Archive etc. for providing important planetary parameters. The Author is also thankful to editor and reviewers for their thoughtful comments.

References

1) Wolszczan A, Frail DA. A planetary system around the millisecond pulsar PSR1257 + 12. *Nature*. 1992;355:145–147. Available from: https://doi.org/10.1038/355145a0.
2) Mayor M, Queloz D. A Jupiter-mass companion to a solar-type star. *Nature*. 1995;378(6555):355–359. Available from: https://doi.org/10.1038/378355a0.
3) Hara NC, Ford EB. Statistical Methods for Exoplanet Detection with Radial Velocities. *Annual Review of Statistics and Its Application*. 2023;10:623–649. Available from: https://doi.org/10.1146/annurev-statistics-033021-012225.
4) Fortney JJ, Dawson RI, Komacek TD. Hot Jupiters: Origins, Structure, Atmospheres. *Journal of Geophysical Research: Planets*. 2021;126(3):1–28. Available from: https://doi.org/10.1029/2020JE006629.
5) Zhu W, Dong S. Exoplanet Statistics and Theoretical Implications. *Annual Review of Astronomy and Astrophysics*. 2021;59:291–336. Available from: https://doi.org/10.1146/annurev-astro-112420-020055.
6) Wright JT, Gaudi BS. Exoplanet Detection Methods. 2009. Available from: https://arxiv.org/abs/1210.2471.
7) Ivanova AE, Yakovlev OY, Ananyeva VI, Shashkova IA, Tavrov AV, Bertaux JLL. The "Detectability Window" Method to Take into Account Observational Selection in the Statistics of Exoplanets Discovered through Radial Velocity Measurements. *Astronomy Letters*. 2021;47(1):43–49. Available from: https://doi.org/10.1134/S1063773721010059.
8) Nelson BE, Ford EB, Rasio FA. Evidence for Two Hot-Jupiter Formation Paths. *The Astronomical Journal*. 2017;154(3):1–11. Available from: https://iopscience.iop.org/article/10.3847/1538-3881/aa82b3.
9) Dawson RI, Johnson JA. Origins of Hot Jupiters. *Annual Review of Astronomy and Astrophysics*. 2018;56(1):175–221. Available from: https://doi.org/10.1146/annurev-astro-081817-051853.
10) Bailey E, Batygin K. The Hot Jupiter Period–Mass Distribution as a Signature of in situ Formation. *The Astrophysical Journal Letters*. 2018;866(1):1–5. Available from: https://doi.org/10.3847/2041-8213/aade90.
11) Alei E, Claudi R, Bignamini A, Molinaro M. Exo-MerCat: A merged exoplanet catalog with Virtual Observatory connection. *Astronomy and Computing*. 2020;31:100370. Available from: https://doi.org/10.1016/j.ascom.2020.100370.
12) Feng F, Anglada-Escudé G, Tuomi M, Jones HRA, Chanamé J, Butler PR, et al. Detection of the nearest Jupiter analogue in radial velocity and astrometry data. *Monthly Notices of the Royal Astronomical Society*. 2019;490(4):5002–5016. Available from: https://doi.org/10.1093/mnras/stz2912.
13) Giertych N, Williams JP, Haravu P. A statistical primer on exoplanet detection methods. 2022. Available from: https://arxiv.org/abs/2205.10417.
14) Horne K. Status and prospects of planetary transit searches: hot Jupiters galore. 2003. Available from: https://arxiv.org/abs/astro-ph/0301249.
15) Mayor M, Lovis C, Santos NC. Doppler spectroscopy as a path to the detection of Earth-like planets. *Nature*. 2014;513(7518):328–335. Available from: https://doi.org/10.1038/nature13780.
16) Dai Z, Ni D, Pan L, Zhu Y. Five Methods of Exoplanet Detection. In: 2021 5th International Conference on Mechanics, Mathematics and Applied Physics (ICMMAP 2021), 23-25 July 2021, Guilin, China;vol. 2012 of Journal of Physics: Conference Series. IOP Publishing. 2021;p. 1–10. Available from: https://doi.org/10.1088/1742-6596/2012/1/012135.
17) Budrikis Z. 30 years of exoplanet detections. *Nature Reviews Physics*. 2022;4(5):290. Available from: https://doi.org/10.1038/s42254-022-00459-x.
18) The Extrasolar Planets Encyclopaedia. . Available from: http://exoplanet.eu/.
19) NASA Exoplanet Archive. . Available from: https://exoplanetarchive.ipac.caltech.edu/.
20) Kane SR, Mahadevan S, Braun KV, Laughlin G, Ciardi DR. Publications of the Astronomical Society of the Pacific Astronomical Society of the Pacific, find out more Refining Exoplanet Ephemerides and Transit Observing Strategies. *Publications of the Astronomical Society of the Pacific*. 2009;121(889):1386–1394. Available from: https://doi.org/10.1086/648564.
21) Udry ST, Mayor M, Santos NC. Statistical properties of exoplanets-I. The period distribution: Constraints for the migration scenario. *Astronomy & Astrophysics*. 2003;407(1):369–376. Available from: https://doi.org/10.1051/0004-6361:20030843.
22) Raymond SN, Izidoro A, Bolmont E, Dorn C, Selsis F, Turbet M, et al. An upper limit on late accretion and water delivery in the TRAPPIST-1 exoplanet system. *Nature Astronomy*. 2022;6(1):80–88. Available from: https://doi.org/10.1038/s41550-021-01518-6.
23) Bonsor A, Harrison J, Shorttle O, Carter P, Kama M, Hollands M, et al. Volatile loss, Differentiation and Collisions: Key to the Composition of Rocky Exoplanets. *European Planetary Science Congress*. 2020;14(EPSC2020-387). Available from: https://doi.org/10.5194/epsc2020-387.
24) Wu DHH, Rice M, Wang S. Evidence for Hidden Nearby Companions to Hot Jupiters. *The Astronomical Journal*. 2023;165(4):1–16. Available from: https://doi.org/10.3847/1538-3881/acbf3f.
25) Mondal S. Classification of Hot Jupiter Population through Statistical Framework. *Journal of Scientific Research*. 2022;14(2):513–519. Available from: https://doi.org/10.3329/jsr.v14i2.56497.
26) Raymond SN, Quinn T, Lunine JI. The formation and habitability of terrestrial planets in the presence of close-in giant planets. *Icarus*. 2005;177(1):256–263. Available from: https://doi.org/10.1016/j.icarus.2005.03.008.

27) Osborn A, Bayliss D. Investigating the planet–metallicity correlation for hot Jupiters. *Monthly Notices of the Royal Astronomical Society*. 2020;491(3):4481–4487. Available from: https://doi.org/10.1093/mnras/stz3207.
28) Yee SW, Winn JN. The Period Distribution of Hot Jupiters Is Not Dependent on Host Star Metallicity. *The Astrophysical Journal Letters*. 2023;949(2):1–7. Available from: https://doi.org/10.3847/2041-8213/acd552.
29) Yu H, Weinberg NN, Arras P. Tides in the High-eccentricity Migration of Hot Jupiters: Triggering Diffusive Growth by Nonlinear Mode Interactions. *The Astrophysical Journal*. 2021;917(1):1–15. Available from: https://doi.org/10.3847/1538-4357/ac0a79.
30) Vick M, Su Y, Lai D. High-eccentricity Migration with Disk-induced Spin–Orbit Misalignment: A Preference for Perpendicular Hot Jupiters. *The Astrophysical Journal Letters*. 2023;943(2):1–10. Available from: https://iopscience.iop.org/article/10.3847/2041-8213/acaea6.
31) Zhang Y, Liu SFF, Lin DNC. Orbital Migration and Circularization of Tidal Debris by Alfvén-wave Drag: Circumstellar Debris and Pollution around White Dwarfs. *The Astrophysical Journal*. 2021;915(2):1–11. Available from: https://iopscience.iop.org/article/10.3847/1538-4357/ac00ae.
32) Van Eylen V, Albrecht S, Huang X, MacDonald MG, Dawson RI, Cai MX, et al. The orbital eccentricity of small planet systems. *The Astronomical Journal*. 2019;157(2):1–16. Available from: https://doi.org/10.3847/1538-3881/aaf22f.
33) Kataria T, Showman AP, Lewis NK, Fortney JJ, Marley MS, Freedman RS. Three-dimensional Atmospheric Circulation of Hot Jupiters on Highly Eccentric Orbits. *The Astrophysical Journal*. 2013;767(1):1–19. Available from: https://iopscience.iop.org/article/10.1088/0004-637X/767/1/76.
34) Ford EB. Architectures of planetary systems and implications for their formation. *Proceedings of the National Academy of Sciences*. 2014;111(35):12616–12621. Available from: https://doi.org/10.1073/pnas.130421911.
35) Santos NC, Adibekyan V, Figueira P, Andreasen DT, Barros SCC, Delgado-Mena E, et al. Observational evidence for two distinct giant planet populations. *Astronomy & Astrophysics*. 2017;603:1–6. Available from: https://doi.org/10.1051/0004-6361/201730761.