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Classification of Hot Jupiter Population through Statistical Framework

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Abstract

The recent trend in the discovery of a range of exoplanets opens up a door to evaluate their origin and classification under the light of different planetary attributes. This paper enthusiastically focused on a typical branch of exoplanets, hot Jupiter, and several planetary characteristics were observed to frame the population into substantive categories. In this paper, a statistical framework was also established to understand different planetary formation processes for hot Jupiters. Finally, the relevance of hot Jupiters in search of habitable planets is also discussed briefly.

Keywords: Hot Jupiters; Planetary formation; Star metallicity; Habitable zone.

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1. Introduction

It is not far back when the concept of planetary systems except our solar system was the only stuff of theory and informed speculation. As time progresses, the catalog of exoplanets and their parent stars gets longer, and it helps mold different models of planetary formation around complex data. A special class emerges from the large pool of exoplanets due to their intriguing characteristics, inflated size, and proximity to the parent star. They are popular under the name of "Hot Jupiter," as during the first quadrant of their discovery period, most of them were found to have a mass comparable to our solar Jupiter [1]. Due to the propinquity of the parent star (semi-major axis <0.1 AU), Hot Jupiters have a concise orbital period (around a few days only) while our solar system Jupiter has a very long period of ~12 years orbits at ~5 AU from the Sun [2,3].

Mayor and Queloz discovered the first hot Jupiter through periodic Doppler shifts caused by the gravitational tug of 51 Pegasi [4]. This technique is biased towards finding hot Jupiters around less massive stars. After two decades since then, there are many more techniques, viz., radial velocity planets and dedicated photometric transits surveys, that have been deployed to detect and probe their physical attributes [5-8]. A group of these planets will have orbital inclinations close enough to edge in so that wide-angle CCD lenses capture the dimness of starlight during their transits in front of its parent star. Stars targeted by ground-based transit surveys are often amenable to radial velocity follow-up

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to establish a collation of the hot Jupiter archive. By combining planet discoveries from various surveys into an updated sample, we may say something more precise about the population statistics of hot Jupiters with respect to their physical parameters.

2. Formation of Hot Jupiters

Prior to the discovery of exoplanets, planet formation theory had been developed around our solar system model. The peculiar characteristics of hot Jupiters forced us to diversify our thoughts. Previous studies have suggested density of smaller planets changes inversely with planetary radius [9,10]. We have extended our study to include all the newly discovered hot Jupiters to verify their validity [11]. Though smaller planets do not exhibit any significant size-density relation, a different regime can be observed for giant planets having a radius comparable to our Jupiter (Fig. 1).

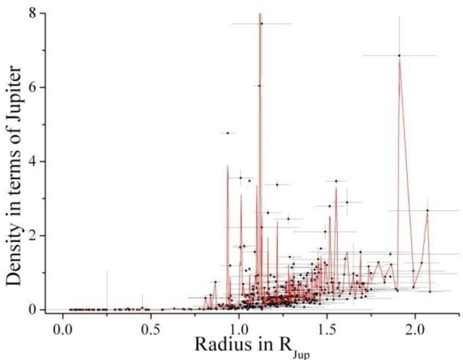

Fig. 1. Variation of planetary density of hot Jupiters *w.r.t.* their size. Red line representing linear trace interpolation of relative densities indicates fluctuation. Everything scaled up to our solar

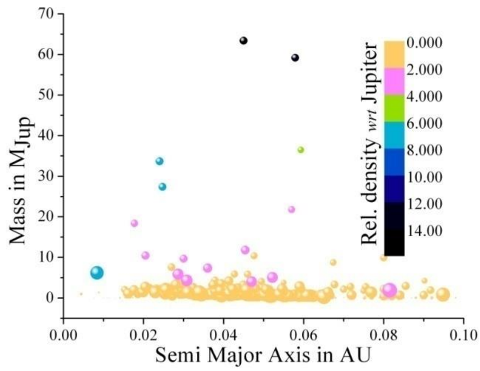

Fig. 2. A study to find correlation between size and their average orbital distance from host star. Radius and density of hot Jupiters are represented by relative size and colour respectively.

Even a reciprocal trend can be found on a close lookup. As for size increases for giants, a steady increment in terms of its density cannot be ignored. Here masses are derived from radial velocity or transit timing variation data available. Inflated size and close proximity to the host star of hot Jupiters imply the presence of a high amount of gaseous components. It is likely to result from the rapid formation of the gaseous atmosphere around before its protoplanetary disk dissipates. Thermal evolutionary atmosphere models deny the *in situ* formation of rocky cores of hot Jupiters [12]. Scientists believe that the formation of a rocky core followed by the accretion of a gaseous envelope starts far away from its parent star, and then it migrated to its current position [13,14]. There are two different theories behind the migration of hot Jupiters. One is based on gradual migration through the gaseous protoplanetary disk [1,13]. It is mainly applicable to the single child planetary system, and the metallicity of the parent star also plays a crucial role in the driving force behind the migration mechanism. The timescale for the inward migration of a giant planet depends on the planet's size and the mass and viscosity of the gaseous disk [15]. The alternative model proposes tidal circularisation after excitation in eccentricity due to any secular perturbation [16,17]. It mainly covers up planetary systems where any planetary scattering occurred due to any perturbation. In both cases, hot Jupiters' density depends on the migration time and metallicity of the protoplanetary disk. However, there are few substantive theories behind the drive of hot Jupiters, but the stopping mechanism is still under mere speculation [18,19]. It has been noticed there is a pile-up of hot Jupiters around 0.3-0.6 AU. Fig. 2 shows most of the hot Jupiters have low density, wrapped up with light gaseous atmosphere irrespective of their sizes. As expected, denser ones are also heavy due to their solid core. But same proportionate relation does not hold for size. In Fig. 2, we can see two super heavy candidates are also the densest members (denoted in black) of the hot Jupiters family, and they are relatively farther away from the host star than other giant ones. It can be assumed that due to close proximity to its host stars, hot Jupiters stripped mass due to stellar irradiation. It results in most of the hot Jupiters are having an average size and low density. Heavier planets are mainly formed over a greater timescale, making them denser than average hot Jupiters. Studies showed massive cores need to reach a critical mass of ~ 10 M_{Earth} to undergo runaway gas accretion before the gas dissipates for heavier disks [20]. Over a critical density limit, the mass-loss rate due to stellar radiation reduces by a margin as the rocky core is always difficult to disintegrate with a gaseous envelope. The apparent abundance of smaller and less dense hot Jupiters near the host star strengthens the irradiation-mass loss theory. These dwarfs have a high chance of annihilation in the future either through accretion onto their host star or by stripping off its leftover mass. The low density of smaller hot Jupiters implies that these planets formed before the gas in the system dissipated completely. The metallicity of the protoplanetary disk determines the rapidness of planetary core formation and chances to accrete a gaseous envelope before the gas in the system dissipates. There are also some other decisive factors in the formation of hot Jupiters that needs to be discussed.

3. Metallicity of the Host Star

The abundance of heavy elements in the photospheres of host stars provides a trail of the chemical composition of the initial protoplanetary disk to its planet [21]. Together with the disk mass, the disk metallicity corresponds to the available amount of planetesimals in the disk for planetary formation. Metallicity, denoted [m/H], is defined as the proportion of a star's outer layers made up of chemical elements other than hydrogen and helium and expressed on a logarithmic scale where zero is the Sun's metallicity. There are different versions of planet-metallicity correlation, but it was observed that the occurrence of gas giant hot Jupiters is nearly proportional to the square of [m/H] [22-25]. This is in good accordance with collision rates of dust particles available in the gas-depleted disk, suggesting its influence on the final existence of a gas giant planet. This model lends weight to the core accretion model [14].

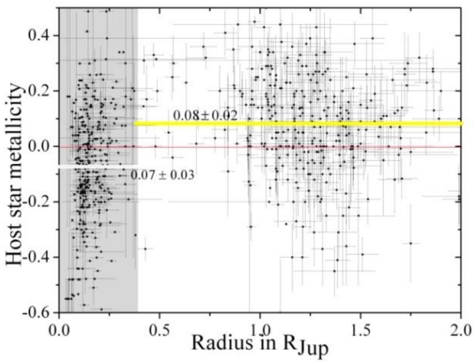

Fig. 3. Study of host star metallicity for hot Jupiters *w.r.t.* its radius. A significant grouping can be observed where Neptunian sized hot Jupiters are around sub solar metallic star and giant ones around super solar.

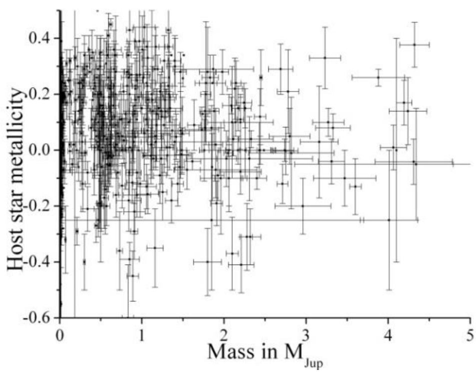

Fig. 4. Dependencies of host star metallicity on formation and size of hot Jupiters through core accretion process was studied. Terrestrial sized planets are crowded in super metallic environment.

To find a correlation qualitatively between the size of hot Jupiters and their parent star metallicity, a study has been done through Fig. 3. Though the distribution of hot Jupiters in the host star metallicity plane is all over, a significant observation can be made through proper sampling. Average metallicity of stars hosting smaller planets having a radius less than Neptune (R_P<$0.4R_{Jup}$) is very much lower (-0.068±0.003) than that of the stars harboring gas giants (0.076±0.002) having a radius greater than the previous class. It is clear from Fig. 3 that smaller hot Jupiters can be observed around a wide range of parent star metallicity, but giants are more likely to be around super solar metallicity. The current study confirms the correlation between metallicity and the possibility of solar-type stars hosting giant hot Jupiters is weaker for Neptunian-sized planets predicted earlier for different planetary samples [26].

As metal-rich stars show the tendency of the increased occurrence rate of planets, it is interesting to investigate the correlation between planetary mass and stellar metallicity also. Fig. 4 exhibits a dense population of lightweight hot Jupiters around positive metallicity. It is relevant to mention that situations for lighter and smaller hot Jupiters are not similar in correlation to host star metallicity. Under the light of Fig. 2, we can observe the scattered distribution of lighter hot Jupiters in the density plane. Most of the terrestrial weighted hot Jupiters are rocky carry out a trace of availability of accretion ingredients in their host star environment. Not all small planets have similar cores due to distance from the host star. They have different gaseous wrapper stripping off rates. So size for smaller hot Jupiters does not significantly correlate with disk metallicity.

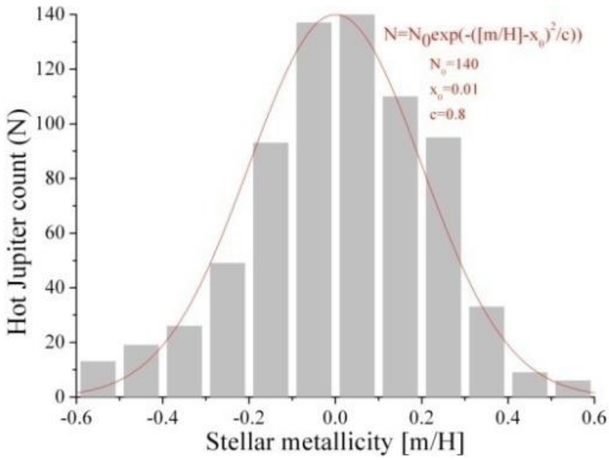

Fig. 5. A representation of frequency distribution regarding the occurrence of hot Jupiters around different metallic stars. The red curve represents regression fit.

Most of the hot Jupiters are found around low metallic stars. Fig. 5 describes their occurrence rate of them in different metallic conditions. I have taken bin width of metallicity 0.01 dex, and the presence of hot Jupiters are found equally shared by sub and super metallic stars. To investigate any relation between hot Jupiters and their parental metallicity, I have deployed regression fitting on occurrence histogram, and it follows as

$$N = 140\exp(-\frac{([m/H]-0.01)^2}{0.8}) \quad (1)$$

where [m/H] and N represents star metallicity measured and no. of hot Jupiters present around it. The coefficient of determination for regression above fit was found 0.9, reflecting a strong correlation between the existences of hot Jupiters with their host star metallicity.

4. Habitable Zone

Previous studies show formation and migration of a giant planet leaves the planetesimal population sufficient time to re-generate in the lifetime of the disk, and terrestrial planets may form adjacently [27]. The character and composition of a system of terrestrial planets are strongly affected by the metallicity of the disk and the presence of one or more giant planets [17]. The habitable zone around a star is defined by the temperature range in that region appropriate for liquid water to exist on the surface of an Earth-like planet. Our solar system is roughly 0.95 - 1.37 AU [28]. Being so near to the host star, hot Jupiters lose their candidature to be a habitable planet. Nevertheless, they can be a good indicator to locate potentially habitable planets. However, other factors play a crucial role in the formation of habitable planets. It has been assumed for the stars having metallicity higher than 0.3 dexes, the probability of hosting a potentially habitable planet drops precipitously

[29]. It drives my search around G-type stars similar to Sun and to the region where planets accompanied by hot Jupiters having a habitable temperature. Measurement or prediction of exoplanets is a complex algorithm, and only 11 % of discovered exoplanets members have registered temperature range till now. Among them, 20 % are around G-type stars. Only seven candidates rise to habitable temperature restriction (200-450 K), and all of them have host star metallicity between -0.1 to 0.3. More than 70 % of them are part of multiple planetary systems, and half of them are accompanied by hot Jupiters. In my result, lack of information on planetary temperature measurement yields small sample data forestalled by the expectation of finding of accompanied hot Jupiters through ongoing planetary search.

5. Conclusion

In this paper, a typical class of exoplanets named hot Jupiters is observed for their abundance in close proximity to host stars. Their migration towards host stars is also scrutinized through different existing models. A strong correlation between size and density has been observed for giant hot Jupiters, but smaller ones disobey it. It has been investigated through the lens of their proximity to the parent star, indicating two different populations in their catalog. A further study considering protoplanetary metallicity strengthens the previous speculation. A progressive study to differentiate them was also done but not included here as it is beyond the scope of this paper. Observations drawn in this paper reveal a connection between the core accretion process of hot Jupiters during migration and their size and density. A distribution study of the metallic environment was done to model accordingly. As the impression of star metallicity is one of the key ingredients for the presence of a habitable zone, an association of finding habitable planets to a hot Jupiter companion may be a great way to lookup.

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