Investigating the Origins of Kepler-1658b's Extreme Density: Heavy-Element Enrichment and Massive Core

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Abstract. Hot Jupiters are a range of hot Jupiters that often challenge standard theories of planetary formation and evolution. They orbit very closely to their host stars, which results in high explosion to intense stellar radiation. Kepler-1658b stands out among hot Jupiters. It has a large mass but a relatively compact radius, which leads to an unusually high mean density. This review brings together current planet models and theories to explore possible explanations for this anomaly. The investigation focuses on three hypotheses: limited radius inflation due to atmospheric mass loss, enrichment in heavy elements throughout the planet's interior, and the presence of an exceptionally large solid core. To test these possibilities, the discussion combines insights from mass–radius models, empirical mass–metallicity trends, and the observed metallicity of Kepler-1658, the host star. Results suggest that atmospheric escape alone is insufficient to explain Kepler 1658b's high density. Instead, heavy-element content and a large core are possible explanations. The review concludes that Kepler-1658b represents an extreme case of internal metal enrichment. This offers valuable opportunities for refining models of gas giant interior structure and formation.

Keywords: Hot Jupiters, Kepler-1658b, Planetary density, Heavy-element enrichment

1. Introduction

Hot Jupiters represent a unique class of exoplanets. They are gas giants and they orbit extremely close to their host stars. As a result, they experience intense irradiation and strong tidal interactions. These extreme conditions are very different from those found in the Solar System, so studying hot Jupiters offers opportunities to test and refine existing theoretical models. Kepler-1658b is one of the first confirmed exoplanets from the Kepler mission. It orbits a metal-rich evolved star Kepler-1658 [1]. With a mass of approximately 5.9 Jupiter masses and a radius close to 1.07 Jupiter radii, it has a high mean density (~5.5 g cm^{-3}) [1]. This density is far above the typical range for hot Jupiters (1–2 g cm^{-}), suggesting that Kepler-1658b has either an unusually large heavy-element content or other physical mechanisms at play [2].

Previous studies have offered references for explaining such anomalies. Guillot discovered that planetary interior models can explain variations in radii by adjusting heavy-element enrichment, often correlating planetary metallicity with stellar metallicity [3]. Fortney et al. developed theoretical radius evolution tracks, showing how planetary radii depend on both mass and incident stellar flux [2]. Thorngren et al. statistically demonstrated that giant planets require significant

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heavy-element enrichment, scaling approximately with planetary mass [4]. These works suggest that Kepler-1658b's unusual density could be explained by extreme enrichment in heavy elements, an oversized core, or a high metallicity fraction in its envelope.

Recent theoretical studies have also highlighted the importance of formation environment in shaping the observed diversity of hot Jupiters. Wang et al. showed that giant planets forming in dense stellar clusters are subject to enhanced dynamical interactions, which can strongly influence their migration histories and final orbital configurations [5]. More recently, N-body simulations by Benkendorff et al. demonstrated that hot Jupiters can form more efficiently in such environments through the combined effects of migration and gravitational perturbations [6]. These results suggest that extreme cases like Kepler-1658b may reflect unique formation pathways. Its anomalously high density may be linked to enrichment processes in a metal-rich or dynamically complex birth environment.

The objective of this paper is to explore why Kepler-1658b has such a high mean density, even under the effects of its close orbit and tidal interactions, which typically lead to inflate radii. To study this question, this paper proposes and examines three possible explanations: atmospheric mass loss through hydrodynamic escape, enrichment in heavy elements relative to solar composition, and the presence of an exceptionally massive core.

2. Method

This work uses a literature-based review approach rather than presenting new observational data. The paper begins by publishing parameters for Kepler-1658b, including its mass, radius, density, orbital parameters, and host star metallicity. These values are taken from Chontos et al. [1]. To give explanations on Kepler-1658b's density, this paper relies on established models: The Fortney et al. planetary radius evolution models, Guillot 's interior structure formalism and Thorngren et al.'s empirical correlation [2-4]. The Fortney et al. planetary radius evolution models are across varying insolation and metallicities [2]. Guillot 's interior structure formalism links planetary radius to heavy-element mass fraction [3]. Thorngren et al.'s empirical correlation is between planetary mass and heavy-element enrichment [4]. These models allow testing whether Kepler-1658b's observed mass and radius are consistent with predictions for a typical hot Jupiter. This paper then analyzes three proposed explanations. The first explanation is atmospheric escape. Hot Jupiters often undergo mass loss due to stellar irradiation. Models such as those by Owen & Wu and Lopez & Fortney provide scaling relations for hydrodynamic escape [7,8]. This paper reviews whether such an escape could reduce Kepler-1658b's radius while maintaining its mass. The next explanation is heavy-element enrichment. Following Thorngren et al., this paper studies the degree of heavy-element mass required to reproduce Kepler-1658b's density [4]. Comparisons with stellar metallicity provide additional constraints. The last explanation is an oversized core hypothesis. Interior modeling [3, 9, 10] allows us to estimate the maximum possible core size for a planet of Kepler-1658b's mass. This paper reviews whether such a large core is consistent with known planet formation scenarios.

3. Results

3.1. Physical parameters of Kepler-1658b

Based on published measurements, Kepler-1658b exhibits properties in Table 1 [1].

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Table 1. Parameters of Kepler-1658b

Parameter	Value
Mass (Mp)	5.88 ± 0.47 MJ
Radius (Rp)	1.07 ± 0.04 RJ
Mean Density (ρp)	~5.5 g cm^{-3}
Orbital Period (P)	3.85 days
Semi-major axis (a)	~0.05 AU
Host star metallicity ([Fe/H])	+0.16 dex

3.2. Comparison with typical hot Jupiters

Most hot Jupiters lie within 0.3–3 MJ and 1.1–1.6 RJ, with densities of 0.5–2.0 g cm^{-3} [2]. In contrast, Kepler-1658b is nearly 6 MJ in mass but only about 1.07 RJ in radius, so it has a density of ~5.5 g cm^{-3}. This value is several times higher than the typical hot Jupiter density range, so Kepler-1658b is extremely dense.

3.3. Radius predictions from theoretical models

Fortney et al. models predict that a 6 MJ planet at 0.05 AU should have a radius of ~1.1–1.3 RJ [2]. The data has a range because it depends on age and heavy-element content. Kepler-1658b's observed radius (1.07 RJ) falls below these expectations, which suggests additional radius suppression mechanisms. Using Thorngren et al. scaling relations, a 6 MJ planet is expected to contain ~100–200 M⊕ of heavy elements [4]. To explain Kepler-1658b's density, the required heavy-element mass would be much larger, potentially exceeding 400 M⊕. These results confirm that Kepler-1658b is unusually compact compared to both theoretical predictions and the observed hot Jupiter population.

3.4. Observational constraints and errors

The inference of Kepler-1658b's unusually high density relies on transit and radial velocity measurements, which constrain its radius and mass, respectively. Chontos et al. derived a mass of ~5.9 MJ with uncertainties of ~10%, and a radius of ~1.07 RJ with uncertainties of ~5% [1]. These measurements are relatively precise, so even small uncertainties in both parameters affect the derived bulk density greatly. Consequently, the reported "extreme" density of Kepler-1658b should be interpreted with caution, because it reflects not only the planet's intrinsic properties but also the limitations of the observational techniques.

4. Discussion

4.1. Atmospheric mass loss

Hydrodynamic escape is a phenomenon driven by intense stellar irradiation. It is a common mechanism that shapes the radii of exoplanets close to their host stars. Mass-loss rates for hot Jupiters are typically 10^9–10^{11} g s^{-1} calculated by scaling laws from Owen & Wu [7]. However, for a massive planet like Kepler-1658b, the gravitational potential is much deeper than that for typical hot

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Jupiters. Its escape velocity (~70 km s^{-1}) makes significant mass loss inefficient, even under strong irradiation. As Lopez & Fortney noted, atmospheric erosion is more effective for sub-Neptunes and Saturn-mass planets [8]. Thus, atmospheric escape is unlikely to be the dominant factor in explaining Kepler-1658b's high density.

4.2. Heavy-element enrichment

A more plausible explanation for the high density is an enrichment of heavy elements within the planet's interior. The required enrichment can be estimated by leveraging the empirical mass-metallicity relation from Thorngren et al. [4]. Their statistical study found that the total heavy-element mass (Mz) in giant planets correlates with planetary mass (Mp) as:

$$\mathrm{Mz} = \left(57.9 \pm 7.03\right) M_{\oplus} \left(\frac{\mathrm{Mp}}{\mathrm{MJ}}\right)^{0.61 \pm 0.08} \tag{1}$$

For Kepler-1658b (Mp≈5.9MJ Mp≈5.9MJ), this relation predicts a typical heavy-element mass of ~150 M⊕. However, to reproduce the observed radius of ~1.07 RJRJ for a planet of this mass and isolation, interior models (e.g., Guillot's) require a much higher heavy-element content [3]. By interpolating within the model grids of Fortney et al. and subsequent works, we find that a total heavy-element mass on the order of 400–600 M⊕ is necessary to explain the extreme density [2]. This value was derived by interpolating within planetary evolution model grids that incorporate the effects of core mass and envelope metallicity on radius evolution. This value is ~3–4 times higher than the statistical trend predicted by Thorngren et al. for a planet of this mass [4].

This large difference shows that Kepler-1658b stands out from the general trend. The planet may have experienced an unusual formation or evolutionary history. One possible scenario is that it accreted planetesimals very efficiently while the disk was still present. Another possibility is that later giant impacts added extra heavy elements to the planet.

Thorngren et al. also reported a positive correlation between stellar metallicity and planetary heavy-element mass [1, 4]. Kepler-1658 has slightly super-solar metallicity ([Fe/H] ≈ +0.18), which could support the idea of a metal-rich planet, but the enrichment required to explain the observed density still appears unusually large compared to expectations.

Classic work by Guillot already emphasized that the distribution of heavy elements between the core and envelope is a central uncertainty in giant planet modeling [3]. More recently, Fortney, Dawson, and Komacek reviewed advances in the study of hot Jupiter interiors and stressed that heavy-element enrichment remains one of the key parameters shaping both bulk density and atmospheric composition [9]. In particular, they noted that atmospheric metallicity can provide indirect evidence for enrichment levels in the deep interior. In the case of Kepler-1658b, current mass and radius measurements alone are not efficient to distinguish between scenarios of an oversized solid core or uniformly enriched envelope. Future atmospheric studies using instruments like JWST and ARIEL may detect signals of metal hydrides, water, or carbon monoxide in the atmosphere. These signals would point to an interior that is unusually rich in heavy elements. Thus, Kepler-1658b provides a critical test case for connecting interior models with atmospheric measurements. It also helps test the upper limits of heavy-element enrichment in hot Jupiters.

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4.3. Oversized core hypothesis

Interior structure models [3,10] suggest that extremely dense hot Jupiters could host large rocky/icy cores. For Kepler-1658b, a core mass of 200–300 $M_\oplus$ could explain its compact radius. However, such a core size approaches the upper limit of what is expected from standard planet formation scenarios. Core-accretion models predict that very massive planets do not accumulate solids efficiently, because once a core passes about 10 Earth masses, runaway gas accretion usually takes over. Therefore, forming an oversized core requires unusual conditions. One option is a protoplanetary disk with very high metallicity, and another option is late giant impacts that added more heavy elements.

4.4. Alternating explanations

Heavy-element enrichment is a strong explanation for the high density of Kepler-1658b, but alternative scenarios must also be considered. One possibility is that the planet has undergone significant atmospheric escape or tidal stripping during its evolution. Chen et al. analyzed the age distribution of hot Jupiter host stars and found that these planets are detected more frequently around younger stars. This suggests that while stellar age increases, survival probability decreases due to tidal decay or mass loss [11]. Mustill et al. reached a similar conclusion, showing that hot Jupiters preferentially occur around kinematically cold and younger stellar populations [12]. These results imply that the unusually high density of Kepler-1658b may partly reflect its advanced evolutionary stage and that it has already lost part of its envelope.

In addition, the external environment could have shaped its evolution. Winter et al. demonstrated that stellar clustering can influence planetary system architectures, raising the possibility that Kepler-1658b's extreme properties are not only a product of interior structure but also of its galactic formation environment [13]. Taken together, these studies suggest that both enrichment at formation and evolutionary processes may have acted to produce the present compact state of Kepler-1658b.

4.5. Combined scenarios

The most likely explanation may be a combination of effects: A significantly enriched envelope due to early planetesimal accretion, a large core formed during the runaway accretion phase, and modest suppression of radius inflation due to lower-than-expected stellar irradiation efficiency. Evolutionary processes may have further modified the planet. Kepler-1658b may thus represent a rare outcome in which multiple processes converge to produce a compact hot Jupiter.

5. Conclusion

This study has investigated the unusual physical properties of Kepler-1658b. It focuses on the mass, radius and density of Kepler-1658b and comparison with other hot Jupiters. The results show that Kepler-1658b is unlike typical hot Jupiters. Most hot Jupiters are inflated and have low density, but Kepler-1658b is compact with a density greater than 5 g cm^{-3}. Such an extreme value is inconsistent with standard evolutionary models, which suggests that common mechanisms, such as atmospheric escape, are insufficient to fully explain its properties. Instead, the planet is likely to contain an exceptionally large fraction of heavy elements. Those heavy elements may potentially lie in a huge core or spread through a highly enriched envelope. These findings highlight that Kepler-1658b represents an outlier within the known exoplanet population.

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A limitation of this study is that the results presented here are interpretive rather than definitive. This paper does not fit models directly to observational data but instead synthesizes prior theoretical and observational results to assess possible explanations. Consequently, its conclusions are limited by the current precision of mass–radius measurements. Future observations are expected to provide significant improvements. Space-based facilities such as JWST will deliver high-resolution atmospheric transmission spectra of transiting hot Jupiters. Such spectra may constrain atmospheric composition and metallicity, and indirectly inform interior models by revealing whether a planet has undergone substantial mass loss or contains signatures of enrichment consistent with a large core. For Kepler-1658b, measurements targeting water, carbon monoxide, and metal hydrides could provide key insights into its composition and test the hypothesis that its high density arises from an anomalously large heavy-element fraction.

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