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Formation of the Hot Jupiter Core in the Early Disk

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Abstract: **This paper explores hot Jupiter core formation much nearer to the star than the traditional *in-situ* model suggests. We propose that the protoplanetary disk and the hot Jupiter core form concurrently during a star's infancy, when cooler temperatures favor agglomeration near the inner disk. Building on the *in-situ* model's core principles, our model estimates inner disk formation at a radial distance of about 1.5 times the stellar radius. Within this dense inner region, the Headwind Effect and the cooler temperatures play a crucial role in the formation of the hot Jupiter core. By utilizing the data available on the NASA Exoplanet Archive[1], we conducted a numerical analysis on six hot Jupiter systems with sufficient data and our findings provide compelling evidence in favor of our hypothesis that — core formation likely occurred within the inner disk region during the early stages of stellar evolution.**

Keywords: **hot Jupiter formation, early stellar development, protoplanetary disk, headwind effect, density enhancement, core assembly.**

1. INTRODUCTION

Due to a dearth of direct observation and lack of angular resolution in our instruments probing far distance exoplanetary systems, our current understanding of the giant hot-Jupiter like exoplanets are impeded by spatial resolution and sensitivity constraints (Batygin, et al., 2016; Poon, et al., 2021; Bailey & Batygin, 2018; Morbidelli, et al., 2023; Heller, René, 2019). While the discovery of hot Jupiters has unveiled a new class of exoplanets, it has also presented fresh challenges to our current understanding of disk formation processes (Haworth, et al., 2016; Andrews, 2021; Manara, et al., 2018; Lee, et al., 2021; Morbidelli & Raymond, 2016).

So far, the prevailing models for hot Jupiter formation are the Disk Migration and the *In-Situ* formation. In the disk migration model scenario, a giant planet forms farther out in the protoplanetary disk and then migrates inwards towards the star (Heller, René, 2019). However, this model struggles to explain how these planets reach such closer orbits without being ripped apart by the star’s tidal forces (Heller, René, 2019; Nelson, et al., 2017).

On the other hand, the *in-situ* model challenges the migration paradigm and it proposes that — hot Jupiters form directly near their stars. This requires giant planet formation mechanisms like gravitational instability or core accretion (Morbidelli & Raymond, 2016) to be efficient in the scorching environment. Core accretion, for example, would need a massive "super-Earth" core to rapidly accrete gas from the star’s intense radiation field (Poon, et al., 2021; Morbidelli, et al., 2023). While

[1] The NASA Exoplanet Archive is an online astronomical exoplanet catalog and data service that collects and serves public data that support the search for and characterization of extra-solar planets (exoplanets) and their host stars. It is part of the Infrared Processing and Analysis Center and is on the campus of the California Institute of Technology (Caltech) in Pasadena, CA (Akeson, et al., 2013).

this theory predicts close-in, low-mass companions, its validity hinges on overcoming challenges related to the specific disk conditions required and the potential influence of stellar radiation on core formation (Heller, René, 2019).

Our research aligns with the *in-situ* model — proposing a novel hypothesis that addresses some of its shortcomings. We explore the possibility of a critical distance within a rotating Giant Molecular Cloud (GMC) — where the balance between the orbital and free-fall velocity of the particles, lead to the formation of a rotating disk around the young star — with an inner radius of approximately 1.5 times the stellar radius. This disk must form at the early stages of star formation — where the temperatures of the young star are relatively lower (Schrader, et al., 2018; Boss, 1998; Min, et al., 2011) and sufficient to allow sticking to take place[2]. Within this dense region — the Headwind effect and the cooler temperatures act together to create a zone where conditions are prime for the formation of these dense structures that may eventually evolve into the formation of hot Jupiter planets within the inner disk.

The rings of Saturn are of prime importance in any explanation of planetary development (Peirce, 1880) and in this paper — our curiosity with respect to the application of the Newtonian Laws in the evolution of stellar systems is rather stimulated than appeased by the famous, but long forgotten essay, "On the Stability of the Motion of Saturn's Rings" which was written by James Clerk Maxwell (1831-1879), in the year 1856 at the Cambridge University. In his essay, Maxwell demonstrated that — the balance between a rotating object's inertia and the gravitational pull of a central mass would determined the stability of the ring (Maxwell, 1859) . As a starting point, the next section will revisit the work of Maxwell to explore how an object's gravity and its inherent inertia would manifest and interact with its orbital velocity to create a stable ring.

By gaining this better understanding from a relatively simple system like Saturn's rings, we will be able to build intuition for the more complex dynamics at play during the formation of a protoplanetary disk around a star. Following this foundation, Section 2 will derive the free-fall velocity of a collapsing cloud under the influence of its own gravity. This crucial parameter will then be leveraged in Section 4 to establish a critical distance from the center of the forming star where the balance between inward and outward forces is carefully poised and is hypothesized to be the preferential location for the formation of the disk and the massive hot Jupiter core.

2. MAXWELL'S RECAPITULATION OF THE THEORY OF A RING OF EQUAL SATELLITES

In the year 1856, Maxwell won the prestigious Adams prize for a seminal essay "On the Stability of the Motion of Saturn's rings" at the Cambridge University. The essay topic required Maxwell to investigate the stability of various configurations of solid, liquid and particulate rings orbiting around Saturn (Maxwell, 1859). Maxwell began his investigation by completely abandoning the theory of a solid or fluid ring, and considered the case of a ring, the parts of which are not rigidly connected, as in the case of a ring of equal and independent satellites (Bittanti, 2015).

To establish the conditions which could govern the stability of the ring, Maxwell then investigated how the gravitational forces between the satellites and the central body, along with their angular velocities, would influence the motion of the satellites within the ring system. His essay contains a splendid passage in which he masterfully sums up his approach as, i.e.:

Suppose the whole ring to be revolving round a central body, and that one satellite gets in advance of its mean position. It will then be attracted forwards, its path will become less concave towards the attracting body, so that its distance from that body will increase. At this increased distance its angular velocity will be less, so that instead of overtaking those in front, it may by this means be made to fall back to its original position. Whether it does so or not must depend on the actual values of the attractive forces and on the angular velocity of the ring. When the angular velocity of the rotating ring is great and the attractive force from the central mass is small, the compensating process will go on vigorously, and the ring will be preserved. When the angular velocity is small and the attractive forces of the ring great, the dynamical effect will not compensate for the disturbing action of the forces, and the ring will be destroyed.

What Maxwell meant was that – depending on the balance between the angular velocity and the gravitational force, the ring may either be preserved or destroyed. He conjectured that – in order for the ring to be preserved, it must rotate at a high

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[2] (Schrader, et al., 2018)'s results indicate that the protoplanetary disk background temperature was much lower at < 503 K during the early stages of formation of our solar system. This was found to be consistent with protoplanetary disk models, which generally predict temperatures < 503 K in the inner disk.

angular velocity while experiencing a weak gravitational force from Saturn. In such a scenario, the outward centrifugal force must act vigorous enough to counterbalance the feeble inward pull, thus preserving the integrity of the ring. Conversely, for the ring to be destroyed, the ring particles must orbit at a low angular velocity while experiencing a strong gravitational force from Saturn. With the slow rotation and strong inward pull, the centrifugal force isn't enough to compensate for the strong gravitational force from Saturn, and the ring will succumb to the attractive force and will be destroyed.

In this present suggested work, our proposed critical distance hypothesis hinges on a similar concept. Within the collapsing protoplanetary nebula, we propose a specific region where the balance between the inward free-fall velocity and the outward orbital velocity of particles creates a favorable environment for disk formation. Building upon the analogy drawn from Maxwell's work, the next section delves deeper by deriving the free-fall velocity of a collapsing Jeans Molecular cloud. This calculation, assuming a rotating cloud at the onset of collapse, will be crucial for establishing the critical distance where the inner disk formation processes might be favored.

3. FREE-FALL VELOCITY OF THE CONTRACTING GMC

In the context of our critical distance hypothesis for core formation, understanding the dynamics of a collapsing protoplanetary nebula is crucial. This section focuses on deriving a free-fall velocity, a key parameter for establishing this critical distance. For a rotating, spherical gas cloud like a young nebula just beginning its gravitational collapse, the characteristic collapse timescale is known as the free-fall time, t_{ff} (Utomo, et al., 2018). To obtain the free-fall velocity from this timescale, we wish to consider a simplified scenario where we have a uniform, self-gravitating GMC collapsing inwards with no external factors like pressure or magnetic fields hindering the collapse. Additionally, we assume the gas and dust are confined within a specific region by the GMC's own gravity. Given that the free-fall time at a pressure gradient in the interior of the clump that is negligibly small is given by:

$$t_{ff}^2 = \frac{3\pi}{32G\rho}, \tag{1}$$

:where G is the Universal Gravitational Constant and ρ is the density of a GMC of mass, M_{cloud} and volume $V = \frac{4}{3}\pi R^3$, as in i.e., $\frac{1}{\rho} = \frac{V}{M_{cloud}}$. The free-fall time can be measured by looking at a particle on the edge of the cloud of radius R:

$$t_{ff}^2 = \frac{\pi^2 R^3}{8GM_{cloud}}.$$

This particle feels an acceleration of $g = -\frac{GM_{cloud}}{R^2}$ from the rest of the cloud by making use of the divergence theorem[3] from electrostatics, whereby the point mass only feels the gravitational force from the mass interior, $M_{cloud} = \frac{\pi^2 R^3}{8Gt_{ff}^2}$ to its radius . The rate of GMC contraction at constant radius is:

$$\lambda_t = \frac{\partial M_{cloud}}{\partial t} = -\frac{\pi^2 R^3}{4Gt_{ff}^3}. \tag{2}$$

Here we introduce a new term called the Compaction Parameter, λ_R, which we define as the gradient between the depleting mass of the GMC and the contracting radius when the rest of the particles free-fall at constant time, i.e.,:

$$\lambda_R = \frac{\partial M_{cloud}}{\partial R} = \frac{3\pi^2 R^2}{8Gt_{ff}^2}. \tag{3}$$

The rate of contraction of a spherical GMC of radius R is therefore obtained by solving the partial differential of λ_t and λ_R as i.e.,:

[3] Divergence Theorem states that — in the absence of the creation or destruction of matter, the density within a region of space can change only by having it flow into or away from the region through its boundary (Christodoulou & Kazanas, 2019).

$$\frac{\partial M_{cloud}}{\partial R} = \frac{\partial M_{cloud}}{\partial t} \times \frac{1}{\frac{\partial R}{\partial t}},$$

$$\frac{3\pi^2 R^2}{8Gt_{ff}^2} = -\frac{\pi^2 R^3}{4Gt_{ff}^3} \times \frac{1}{\frac{\partial R}{\partial t}},$$

$$-\frac{3t_{ff}}{2R} = \frac{1}{\frac{\partial R}{\partial t}},$$

$$\frac{\partial R}{\partial t} = -\frac{2R}{3t_{ff}}.$$

Finally, our free-fall velocity is given by:

$$V_{ff} = -\frac{2R}{3t_{ff}}. \quad (4)$$

Eq. (4) marks the center of our investigation, which focuses on investigating the stability criteria of a young disk, when a knife-edge balance exists between the free-fall and the orbital velocity of the particles making-up the disk. In the next section, we shall leverage the free-fall velocity to obtain the mass of the core of the nascent star formed.

4. GAUSS LAW APPLIED TO A POINT-LIKE SELF-GRAVITATING MASS

To deduce the mass of the core, M_{core}, that must be located at the center of a compact GMC of rotating gas and dust, we consider the structure of the GMC's core in the form of a Gaussian surface S, of radius R_{core}:

$$\oint_S \mathbf{g}.\mathbf{n}\, dA = -4\pi G M_{core}. \quad (5)$$

Everywhere on the surface of the sphere; **g . n** = - g. Vectors **g** and **n** are anti-parallel, with the gravitational flux due to the core pointing inwards, and the normal to the surface **n** pointing outwards (Christodoulou & Kazanas, 2019; Smith, 2008). Since g, is obtainable from the scalar product of the two vectors, then:

$$-g \oint_S d\,A = -4\pi G M_{core}.$$

For a free-fall acceleration of $g = \frac{2R_{core}}{3t_{ff}^2}$, the total surface area of the core is given by the surface integral of the sphere $S = 4\pi R_{core}^2$, i.e.,:

$$-\frac{2R_{core}}{3t_{ff}^2}.4\pi R_{core}^2 = -4\pi G M_{core}.$$

Therefore, the mass of the core strongly depends on the radius of the cloud and the characteristic free-fall timescale:

$$M_{core} = \frac{2R_{core}^3}{3Gt_{ff}^2}. \quad (6)$$

Eq. (6) gives us the mass of the core of the young star. Although gravity acts throughout the entire cloud, the core becomes the densest region due to its central location and the inward pull. This increased density translates to a stronger gravitational pull compared to the outer regions. As the core gets denser, its gravity becomes more dominant. This stronger pull on the surrounding material accelerates the inward collapse, particularly in the regions closer to the core. Therefore, according to Eq. (6), the heavier the core, the less the characteristic free-fall time. In the next section, we will utilize Eq. (4) and Eq. (6) to explain how the disk will form around the protostar.

5. THE STELLAR SYSTEM EVOLUTION

So far — the most widely accepted explanation for the formation of the protoplanetary disk is that — during the star formation processes, material within the GMC is expected to collapse inwards by gravity, towards the core, where a young protostar is forming. The collapsing cloud initially has random motion and orientation of gas and dust particles. However, as the cloud collapses, any net rotation causes the material to flatten into a disk shape due to conservation of angular momentum (Wurster & Li, 2018; Zhao, et al., 2020). The cloud's angular momentum is distributed amongst the particles, and as they come closer to the protostar's center, they rotate around it in a coherent manner. The material that cannot be accreted by the protostar forms a rotating, flattened disk structure surrounding it (Haworth, et al., 2016).

Protoplanetary Disk Formation

Here we simply want to ask and answer the question: Within the collapsing nebula, at what specific distance from the nascent protostar does the balance between gravitational attraction and centrifugal force facilitate the formation of the early disk?

To that end, let the free-fall velocity ($V_{ff} = -\frac{2R}{3t_{ff}}$) represents the inward gravitational pull towards the centre of the core, while the orbital velocity ($V_{orb} = \sqrt{\frac{GM_{core}}{R_{orb}}}$) reflect the outward centrifugal force. For the disk to form, we propose a scenario where these velocities fall within a specific range as, i.e.,:

$$V_{ff} < V_{orb}, \quad (7)$$

So that:

$$-\frac{2R}{3t_{ff}} < \sqrt{\frac{GM_{core}}{R_{orb}}}. \quad (8)$$

This means that — the gravitational pull from the nascent star, induces a free-fall motion towards the center. However, as particles fall inwards, they also acquire an orbital velocity, due to the rotation of the collapsing cloud. An outward centrifugal force which opposes the inward pull develops. In-principle, particles with orbital velocity greater than the free-fall velocity are resistant to inward collapse thus they remain in stable orbits, ultimately contributing to the formation of the protoplanetary disk at a certain critical distance from the core of the star. To establish this critical distance, let us simplify Eq. (8), such that:

$$\frac{2R}{3t_{ff}} > -\sqrt{\frac{GM_{core}}{R_{orb}}}. \quad (9)$$

Substituting $g = \frac{2R}{3t_{ff}^2}$ into (9) gives us:

$$\frac{2G}{3R}\left(\frac{2R^3}{3Gt_{ff}^2}\right) > \frac{GM_{core}}{R_{orb}}.$$

Hence, for constant λ_R, $R = R_{star}$ and:

$$R_{orb} > 1.5R_{star}. \quad (10)$$

What this obviously means is that the interaction between gravitational attraction and orbital motion plays a crucial role in the formation of the protoplanetary disk. Eq. (10) suggests that the inner disk must form at a distance of $R_{inner} = 1.5R_{star}$. Particles located beyond this distance can achieve stable orbital trajectories due to the balance between the inward pull of gravity and the outward centrifugal force arising from the disk's rotation.

The Growth of the Nascent Star's Core

If a condition contrary to (7) was to establish within the GMC — where the free-fall velocity of the particle is greater than the orbital velocity, as i.e.,:

$$V_{ff} > V_{orb},$$

then:

$$-\frac{2R}{3t_{ff}} > \sqrt{\frac{GM_{core}}{R_{orb}}},$$

and surely this condition must sum up-to:

$$R_{orb} < 1.5R_{star}.$$

This means that — during these early stages of star formation, the collapse of a GMC triggers the simultaneous formation of the protoplanetary disk. Particles with free-fall velocity, $V_{ff} > V_{orb}$ or with inherently lower initial velocities will experience a stronger inward pull than the outward centrifugal force arising from the nascent disk's rotation. This imbalance prevents them from achieving stable orbits within the forming disk. Consequently, these particles succumb to the dominant inward pull and spiral inwards, ultimately free-falling onto the young star's surface.

Hot Jupiter Core Formation due to the Headwind Effect

Within the dynamic environment of a protoplanetary disk, a phenomenon known as the Headwind Effect is known to play a critical role in the initial stages of planet formation. This effect arises due to the interplay between the settling of dust grains towards the central star and the differential orbital velocities within the disk governed by Keplerian rotation (Kuwahara & Kurokawa, 2020). Eq. (7) has already suggested that — during the early stages of disk evolution, particles which lose their angular momentum, end up orbiting at velocities which are near equal to the free-fall velocity, i.e., $V_{orb} \cong V_{ff}$. Particles with $V_{ff} < V_{orb}$ remain in stable orbit within the disk. These particles with $V_{orb} \cong V_{ff}$, experience a drag force that originates from the faster moving particles orbiting near the inner disk.

Due to the high orbital velocities of particles near the inner edge of the disk, the headwind effect preferentially targets these smaller, less massive particles, hindering their inward drift and giving them enough time for agglomeration. This agglomeration facilitates the formation of a density enhancement which then grows into a large and denser body that can eventually overcome the headwind's influence and continue their journey towards the inner disk area, where the inner core of the Hot Jupiter could potentially grow.

The disk undergoes Keplerian motion and if this core is to sweep through the inner disk with the highest possible efficiency, it – surely – must have the smallest orbital period within the disk. What this obviously means is that, the core ought to be located near the innermost edge of the disk, where it will be able to quickly graze through the critically unstable disk eating up all the disk material in its way within its gravitational sphere of influence. As the core's mass increases, so does its gravitational sphere of influence – hence its capture near the star.

Table 1: Table of R_{orb} for known stellar systems (WASP -12, WASP - 33, KOI - 13, HAT - P -7, HAT - P - 13, HAT - P - 70) with hot Jupiter planets orbiting closer to the central star.

Host Star	Solar Radius	Hot Jupiter	a	R_{orb}	Reference
	($R_{\odot}$)	(Closest Planet)	(AU)	(AU)	
WASP - 12	1.75	WASP- 12b	0.023	0.012	(1,2)
WASP - 33	1.60	WASP - 33 b	0.024	0.011	(3,4)
KOI-13	2.68	KOI-13 b	0.036	0.019	(5,6)
HAT-P-7	2.00	HAT-P-7 b	0.032	0.014	(7,8)
HAT - P- 13	1.91	HAT - P- 13 b	0.043	0.013	(9,10)
HAT- P - 70	1.97	HAT-P-70 b	0.047	0.014	(11,12)

References: 1. (Chakrabarty & Sengupta, 2019), 2. (Chakrabarty & Sengupta, 2019), 3. https://exoplanetarchive.ipac.caltech.edu/overview/wasp-33, 4. (Chakrabarty & Sengupta, 2019), 5. (Batalha, et al., 2013), 6. (Esteves, et al., 2015), 7. (Bonomo, et al., 2017), 8. (Winn, et al., 2009), 9. https://exoplanetarchive.ipac.caltech.edu/overview/HAT-P-13, 10. (Turner, et al., 2016), 11. https://exoplanetarchive.ipac.caltech.edu/overview/HAT-P-70, 12. (Zhou, et al., 2019) .

6. GENERAL DISCUSSION AND CONCLUSION

This paper suggests that — the formation of hot Jupiters can clearly be understood within the context of early stellar formation. Drawing from our Critical Distance Hypothesis — the rocky core forms near the inner edge of the early protoplanetary disk due to the Headwind Effect which we characterized by differential rotation and potentially near free-fall velocities ($V_{orb} \cong V_{ff}$). This Headwind Effect and the lower temperatures present at these early stages, enable a massive density enhancement to form much more efficiently through enhanced collisions. This massive density enhancement would overcome the headwind's influence and migrate inwards towards the inner disk to form the much needed rocky core for the

Hot Jupiter to start forming. Perhaps to show the possible value of this proposed work, Table 1 presents calculations for six exoplanetary systems known to harbor hot Jupiters. These hot Jupiters orbit their stars with semi-major axes ranging from 0.023 to 0.047 AU. Based on Equation Eq. (10), these exoplanets might have formed near the inner region of the disk at a critical distance of R_{orb} from the centre of the nascent star. As an example, Table 1 explores the WASP-12 stellar system whose data was extracted from the NASA Exoplanet Archive at https://exoplanetarchive.ipac.caltech.edu/overview/wasp-12. Here, calculations suggests that — an inner protoplanetary disk potentially formed at a critical distance of 0.012 AU from the star. This implies that the hot Jupiter, WASP-12b, could have formed near this dense region. However, observations place WASP-12b's current orbit at 0.023 AU. This discrepancy between predicted formation zone and observed orbit might be explained by the headwind effect and turbulence. These factors could influence the penetration depth of the material formed outside the headwind's influence, with larger or denser particles experiencing deeper penetration and settling closer to the inner disk compared to smaller ones.

7. LIMITATIONS

Our proposed model for hot Jupiter core formation acknowledges limitations that require further investigation. While our numerical analysis, as shown in Table 1, lends support to the *in-situ* formation for hot Jupiters, our proposed model falls short in fully accounting for the disparity observed with planet Mercury which is the innermost planet in our solar system. Our model places a hot Jupiter at a distance of 0.01 AU from the sun, whereas Mercury orbits at a significantly greater distance of 0.4 AU. These limitations highlight the need for a follow-up investigation (Part II: On the Plausible Condition(s) for Disk Collapse Leading to Planet Formation) that utilizes simulations and detailed analysis to address these challenges and solidify the feasibility of hot Jupiter core formation at close proximity to the nascent star.

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