

# Unveiling the Formation and Evolution of Massive Planets

Zichong Wen

Qinghua Zhiqing International, Beijing, 100084, China  
woodywen@ldy.edu.rs

## Abstract:

Research into the formation of massive planets is crucial for understanding the evolution of planetary systems and assessing the potential for habitable environments on exoplanets. Despite the growing body of research, there remains a gap in comprehending the complexities of how these massive bodies form, migrate, and interact with their host stars. This study aims to fill that gap by investigating the processes underlying the formation and evolution of massive planets. Focusing on the role of gravitational forces, internal structures, and atmospheric compositions, the research delves into the core accretion model and the disk instability model, both of which offer insights into planetary formation mechanisms. The study also examines the migration patterns of massive planets and their effects on surrounding celestial bodies, particularly within the context of protoplanetary disks and stellar radiation. The interactions between massive planets and their host stars are also analyzed, highlighting the impact of tidal forces and magnetic field interactions. The research findings confirm that massive planets play a critical role in shaping the dynamics of planetary systems, acting as “guardians” that influence the stability and evolution of other planets. The study concludes that understanding these massive planets’ formation and behavior is essential for developing more accurate models of planetary systems and advancing the search for extraterrestrial life.

**Keywords:** Planetary Formation, Core Accretion Model, Massive Planets, Planetary Migration, Protoplanetary Disks

## 1. Introduction

There are relatively fewer massive planets compared to other types, and their formation also requires more time. The mass of a planet is one of the most significant factors used to characterize it, as a planet’s mass and size determine the strength of its gravitational force. By studying massive planets, scientists can gain insights into the complexities of planetary systems and uncover important clues for identifying and evaluating habitable environments on exoplanets.

The significant gravitational force and complex internal structures of massive planets make them valuable objects of study in planetary physics. Research into these planets allows scientists to better understand the pressure and temperature distributions within them, as well as their core compositions. Such information is essential for developing accurate models of planetary formation and evolution. Massive planets usually have thick atmospheres rich in hydrogen, helium, and other gases. Studying the composition and structure of these atmospheres can reveal the processes by which planets accrete gases early in their formation, as well as understand how phenomena such as atmospheric escape affect planetary evolution.

The presence of massive planets confirms the core accretion model of planet formation, in which dust and gas gradually accumulate to form a solid core in a protoplanetary disk, followed by core accretion of large amounts of gas to form an atmosphere. This model is crucial for understanding how planets form, especially gas giants like Jupiter and Saturn

The migration of massive planets in planetary systems is an important field in the study of planetary dynamics. Massive planets may have orbital migrations through interactions with gas and other planets in the disk, which could explain the proximity of giant planets to stars in some exoplanet systems. Massive planets may play the role of “guardians” in planetary systems. Jupiter, for example, through its powerful gravitational effect, can capture or alter the trajectory of comets or asteroids entering the inner solar system, thereby reducing the frequency of these objects impacting terrestrial planets, which to some extent protects life on Earth. Likewise researching other massive exoplanets provides the possibility to find planets that support life.

By researching massive planets, people Reveal the formation process and evolution mechanism of planets. Due

to the powerful gravity of the massive planets, they will affect the stability of other orbits. Massive planets, especially those that are very close to their star as “hot Jupiters,” may influence the activity level of their star through tidal interactions or magnetic field interactions. This could change the star’s rotation rate or magnetic field strength, which could indirectly affect the evolution of the entire planetary system.

The mystery of the formation and evolution of massive planets is how to accurately describe their formation through core accretion, disk instability, or other mechanisms, and explain the complexity of their orbital migration, internal structure, and atmospheric composition. This paper focuses on the formation of massive planets and hopefully contributes to these mysteries. This research not only enhances the understanding of the history of our solar system but also plays a crucial role in the ongoing search for extraterrestrial life in the universe.

## 2. The Basics of Planetary Formation

There is already some research about the formation of massive planets and the reason why it is formed. For example, the research of “Armitage PJ” about how planets were formed. The dust around the star is critical to forming celestial objects around it. Carbon and iron in these dust are the factors that form planetary systems. When a star forms its disk, known as the T Tauri phase, it spews out scorching winds that consist mostly of positively charged protons and neutral helium atoms. Although most of the material from the disk is still falling on the star, a small group of lucky dust particles is colliding with each other and clumping together into larger objects. There is a threshold concerning the mass of planets, to be more specific, only two to three planets have exceeded this threshold. The research is going to determine the properties and traits of these planets that differ from others.[1]

The research of planet formation is closely related to other fields of astronomy due to its rootedness. All the planets that existed were developed from the very beginning. To study the properties of those planets, scientists are most likely to speculate them through the very beginning as well. The planet’s formation also helps in learning some of the anomalies or traits that a specific one possesses. People always use Jupiter-mass as a unit to measure an exoplanet. Objects in the 0.3 mjup-60 MJup range follow a close linear relationship, with no distinct traits to differentiate the low-mass end (giant planets) and the high-mass end (brown dwarfs). A large planet is defined as a substar that does not experience burning temperatures during its lifetime. Measured at this baseline, the boundary between the planet and the brown dwarf is approximately 13mjup.

However, this distinction seems arbitrary, as there is no such limit for distributions of Von Musikstar over 25mjup [2].

## 3. Massive Planets and Their Characteristics



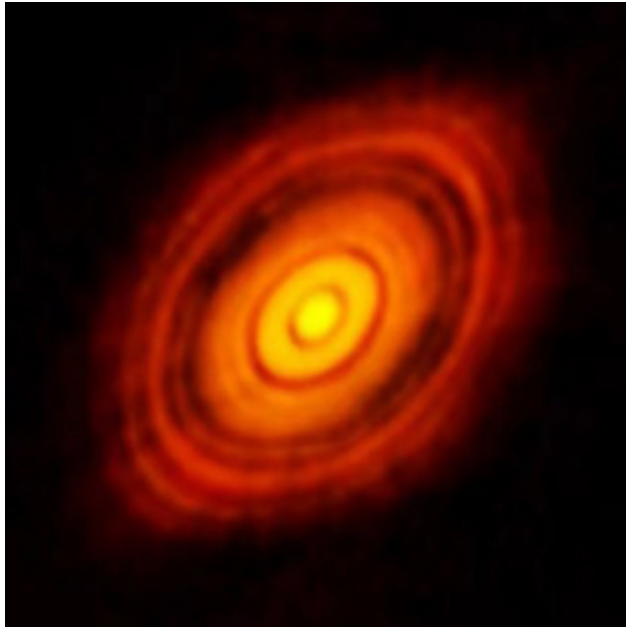
**Fig. 1 Illustration of a model showing how gas giants such as Jupiter, Saturn, or Uranus could form quickly in the solar system from the dust of a protoplanetary disk and then drive dust into areas outside their orbit [3].**

### 3.1 Factors Influencing Massive Planet Formation

The formation of extremely massive planets requires tiny particles low to millimeters that orbit along with gas in protoplanetary disks around young low-mass stars. These disks are common among planets and persist for a long period until it ruins. Young planets gradually absorb these celestial bodies as they orbit their host star, leading to the accumulation of dust and asteroids that eventually merge to form a planet. Fig. 1. shows an Illustration of a model showing gas giants such as Jupiter, Saturn, or Uranus forming. However, a notable observation arises: some planets, despite being of similar age to others, possess greater mass than those that have likely been orbiting their host stars for longer periods. According to my research, these more massive planets with larger radii are consistently located in the central region of their respective systems—neither too close nor too distant from their host star [1]. Moreover, the formation of massive planets, such as gas giants like Jupiter and Saturn, also involves several special factors that distinguish them from smaller, terrestrial planets.

Firstly, the Protoplanetary Disk Conditions. Like the Abundance of Gas and Dust, Massive planets form in regions of the protoplanetary disk where there is a high density of gas and dust. Fig. 2. is a picture of Protoplanetary Disk. This abundance is crucial for building up a large core quickly, which is necessary to attract and retain a thick atmosphere of hydrogen and helium. The lifetime of

the disk is also one of the factors. This is because the gas in the protoplanetary disk must persist long enough for the planet to accumulate its massive envelope. If the gas dissipates too early, the planet will remain small.



**Fig. 2 Atacama Large Millimeter Array image of HL Tauri [4].**

Second, the Core Accretion Process. The formation of a massive planet always requires Rapid Core Formation. For a massive planet to form, a solid core of about 10 Earth masses for example typically needs to form quickly. This core then starts to accrete gas from the surrounding disk. Moreover, Once the core reaches a critical mass, it undergoes runaway gas accretion, rapidly pulling in large amounts of gas to form a massive envelope.

Third, Massive planets often migrate from their original formation locations. They may move closer to or farther from their star, influenced by interactions with the protoplanetary disk or other planets. This migration can affect the final mass and composition of the planet.

Fourth, the Gravitational Interactions. Massive planets can influence each other's orbits through gravitational interactions. These interactions can lead to changes in orbital eccentricity, inclination, and even the eventual merging of planets.

Fifth, the location where it was formed. According to the research, massive planets typically form beyond the "frost line," where temperatures are low enough for volatile compounds like water, ammonia, and methane to condense into solid ice grains. The availability of these ices provides more material for the rapid growth of a planetary core [5].

Then is the accretion of Gas, the accreted gas must cool

and contract for the planet to become massive. This cooling process allows the gas to settle into a stable, massive atmosphere around the solid core.

Seventh, the Orbital Resonances. If a massive planet enters into a gravitational resonance with another planet, this can significantly affect its orbital evolution and sometimes lead to enhanced accretion rates or even the capture of additional material.

Gravitational Instability is also one of the factors that affect planetary formation. According to the "Disk instability Model, planets can form through the direct gravitational collapse of a region of the protoplanetary disk. In this scenario, a dense clump of gas in the disk collapses under its gravity to form a planet, bypassing the need for core accretion [6].

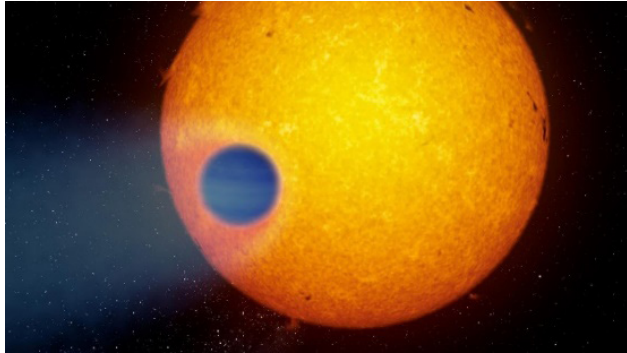
### **3.2 The Impact of Stellar Characteristics on Planetary Mass and Measurement Techniques**

According to the research, the evolution of the mass of a planet is strongly related to the physical properties of its host star. The past activities of the host star can therefore affect the overall population of the planet in a system. But what's important in this paper is how it affects planetary mass.

To begin with, the evolution of planetary hydrogen-dominated atmospheres is controlled by the thermal evolution of the planet. The loss and growth in its atmospheric mass are strongly associated with the stellar environment of the planet. Including the heating of the host star and the amount of energy radiation received by the planet. These two factors both depend on the type of host star and the orbital distance to the planet. Therefore these are also two factors that affect the mass of a planet [7].

In addition, the Stellar Radiation and Photoevaporation also affect planetary formation. Young stars emit intense ultraviolet (UV) and X-ray radiation. This high-energy radiation can heat the upper layers of a planet's atmosphere, causing it to evaporate and escape into space in a process known as photoevaporation, which is particularly significant for low-mass planets or planets with thick atmospheres, like gas giants. Fig.3. is an illustration of an exoplanet named WASP-69b being heated by its host star. If a planet is too close to its host star There are relatively fewer massive planets compared to other types, and their formation also requires more time. The mass of a planet is one of the most significant factors used to characterize it, as a planet's mass and size determine the strength of its gravitational force. By studying massive planets, scientists can gain insights into the complexities of planetary systems and uncover important clues for identifying and evaluating habitable environments on exoplanets. This

research not only enhances our understanding of the history of our solar system but also plays a crucial role in the ongoing search for extraterrestrial life in the universe.



**Fig. 3 This artist's illustration shows WASP-69b, which sits about 163 light years from Earth, orbiting its host star. Credit: Gabriel Perez Diaz, SMM (IAC) [8].**

The significant gravitational force and complex internal structures of massive planets make them valuable objects of study in planetary physics. Research into these planets allows scientists to better understand the pressure and temperature distributions within them, as well as their core compositions. Such information is essential for developing accurate models of planetary formation and evolution, it can lose a significant portion of its atmosphere, reducing its overall mass.

The Solar Wind and Stellar Winds also affect how planets are formed. The host star's stellar wind—streams of charged particles ejected from the star—can strip away a planet's atmosphere over time. This is especially true for planets without strong magnetic fields to deflect the stellar wind. For planets in close orbits, the combined effect of stellar winds and radiation can lead to significant atmospheric erosion, ultimately reducing the planet's mass.

Current techniques for calculating planetary mass face certain limitations. The primary method employed by scientists is radial velocity, where stars, influenced by the gravity of an orbiting planet, exhibit oscillations in small orbits. This allows scientists to deduce the relationship between the mass of a planet and that of its star. Radial velocity proves effective for very large planets, such as Neptune, or for smaller planets akin to Earth, particularly when orbiting bright stars. However, for planets located farther from their stars, similar to Earth, this technology has demonstrated less success. Researchers at MIT have developed a new technique for determining the mass of extrasolar planets by analyzing their transverse signal—immersed in light when a planet transits in front of its star. Traditionally, this data has been utilized to ascertain a planet's size and atmospheric properties. However,

the MIT team has innovated a method to interpret these signals in a manner that also reveals the planet's mass. Additionally, scientists have employed light transmission spectra to calculate planetary mass. A transmission spectrum is formed as a planet transits its host star, allowing some light to pass through its atmosphere. By analyzing the wavelengths of this transmitted light, scientists can infer a planet's atmospheric properties, such as the density and temperature of atmospheric molecules. From the total amount of blocked light, they can subsequently estimate the planet's size and mass [9]. Despite these advancements, existing techniques still face limitations. Stellar activity, including spots, flares, or pulsations, can introduce noise that either mimics or obscures the signal, complicating the detection and accurate measurement of the planet's mass. Addressing these issues requires the enhancement of instruments, extended observation periods, and the development of advanced data analysis techniques.

## 4. Conclusion

The paper discusses the challenges and methodologies related to measuring the mass of large planets, highlighting the complexities involved in planetary formation and the influence of a host star's activities on a planet's mass. The formation of massive planets involves complex processes such as rapid core formation, gas accretion, and gravitational interactions within protoplanetary disks. Additionally, factors such as stellar radiation, solar winds, and photoevaporation significantly impact a planet's mass. The paper also addresses the limitations of current techniques, such as radial velocity, and underscores the necessity for advanced instruments and methodologies to enhance the accuracy of planetary mass measurement. This includes leveraging transmission spectra and accounting for stellar activity. Research into planetary formation not only aids scientists in discovering new astronomical phenomena but also plays a crucial role in identifying potentially habitable planets. Understanding planetary formation and evolution enables researchers to better predict life-supporting conditions, refine models of planetary systems, and improve the search for Earth-like exoplanets that may harbor life.

## References

- [1] Armitage PJ. A trap for planet formation. *Science*. 2013, 340(6137): 1179-80.
- [2] Howard AW. Observed properties of extrasolar planets. *Science*. 2013, 340(6132): 572-6.
- [3] Thomas Zankl. By Ludwig Maximilian University of Munich, August 6, 2024, 2024/9/26 <https://scitechdaily.com/secrets-of-rapid-planet-formation-protoplanetary-puzzles->

solved-at-hyper-speed/

[4] Atacama Large Millimeter Array 1995. Cited 2024/9/26  
[https://en.m.wikipedia.org/wiki/Protoplanetary\\_disk](https://en.m.wikipedia.org/wiki/Protoplanetary_disk)

[5] Shah O, Alibert Y, Helled R, Mezger K. Internal water storage capacity of terrestrial planets and the effect of hydration on the MR relation. *Astronomy & Astrophysics*. 2021, 646: A162.

[6] D'Angelo G, Lissauer JJ. Formation of giant planets. arXiv preprint arXiv:1806.05649. 2018.

[7] Kubyshkina D, Vidotto AA. How does the mass and activity

history of the host star affect the population of low-mass planets?. *Monthly Notices of the Royal Astronomical Society*. 2021, 504(2): 2034-50.

[8] Dana B. How Do planets form? NASA, 2024/5/2, 2024/9/2  
<https://science.nasa.gov/exoplanets/how-do-planets-form>

[9] Gabriel Perez Diaz, SMM (IAC) Dakotah Tyler, The Conversation Published: May 8, 2024 2024/9/26  
<https://www.astronomy.com/science/wasp-69b-and-its-weird-tail-help-us-understand-the-cosmos/>