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The Evolution of Angular Momentum from Terrestrial Planets during their Planetary Formation

Chonglun Xu

Faculty of Science, The university of Hong Kong, Hong Kong, China

u3583473@connect.hku.hk

Abstract. It has been a long run on searching for the angular momentum development and its origin for the terrestrial planets, in contrast to a general theory or equation that can write the whole picture of the angular momentum development. Generally, planetary angular momentum is built up by numerous rocky or dust contributors fused together and affected by later interactions of different sources. In other words, it requires tremendous calculation on the demotion of each debris on a complex system, meaning various theories to study the physics and fit into present observational data. The case of terrestrial planets is studied by computer simulation with models that contain different strategies of interacting bodies inside the space, and these simulations are conducted under various initial conditions, for instance, the number of involving bodies and the sizes of the rocky debris. This article briefly gives a picture of the theories simulating and predicting the development and origin of terrestrial planets by literature view of listed references, aiming to summarize and discuss the differences of several simulations and their conditions.

Keywords: angular momentum, planetary spin, pebble accretion, stochastic accretion.

1. Introduction

The formation of a protostar occurs within a hot in transparent nebula composed of gases and dust, driven by gravitational forces under fragmentations. The initial rotation and gravitational accretion of the protostar facilitate the concurrent movement of surrounding dust and gases towards it, resulting in the creation of a protoplanetary disk and coplanarity of the system. Over millions of years, the materials within this disk undergo gravitational processing, transforming into pebbles and small rocks, which subsequently coalesce into planetesimals measuring several kilometers in size. The interactions of these planetesimals gives rise to the build-up of an early smaller and lighter embryo within the protoplanetary disk. However, the early dynamics like spin of the planets has long modelled into theories under different debates due to multiple challenges in tracing the influences on their rotation since their formation approximately 4.5 Giga-years before. Researchers generally conclude the long-term dynamics from a terrestrial planet to be influenced by various factors, including the initial rotational gain from planetesimal accretion and subsequent significant impacts within the stellar system just like the planet-planet interactions, in addition, it is yet a question to determine the dynamic and future orbits of planets are in stability. Comparing to old theories—core accretion--built from 1960s to 1990s, Many current papers suggest that the spin generated from accretion alone is insufficient to account for the angular momentum of later planets, with the giant-impact theory currently being favored as a more plausible

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explanation for the additional spin. This essay will succinctly explore the origins of terrestrial planetary spin, emphasizing the interplay between accretion processes and later giant impacts contributors, as well as examining spin—retrograde or prograde--and the obliquity compared to the coplanarity axis, with the aim to provide a framework for understanding the dynamical evolution of planets.

2. Accretions lead to the formation of planetary bodies

2.1. Pebble accretion

Retrospectively to the historical theories of planet formation, Laplace's theory believes that planetary bodies are built from gaseous rings, it is reasonable to regard it as the starting of the later planetesimal accretion theories named by Chamberlin. Most terrestrial planetary bodies originate from protoplanetary disks located in the inner regions of the stellar system, thereby inheriting their angular momentum to be clockwise or anticlockwise from an add-up of individual materials from their disk. Fundamental components in protoplanetary bodies typically consist of kilometer-sized planetesimals, which are rocky particles that accumulate due to a significant cross-sectional area. In fact, a dynamically stable planetesimal disk predominantly results in a retrograde planetary spin, while the highest prograde contribution is observed when planetesimals exhibit moderate dynamical excitation, causing their scale height to exceed the Hill sphere curved by the mass of planetary body. Past researchers have concluded that enough prograde spin cannot be built unless the system with a non-uniform disk of planetesimals [1]. Standing on the failed predictions of planetesimal hypothesis, a specific type of accretion involves the accumulation of angular momenta of planetary embryo within small pebbles, as these minute rocks move towards the center of the system alone different layers of disks due to interactions of gas. In contrast to the older version of rapid accretions, pebble accretion suggests the building block scaling from millimeters to centimeters instead of kilometer-sized planetesimals, in addition to the size, the pebbles will maneuver into the center of systems comparing to the accumulations of planetesimals flowed together into individual belt, the result from these smaller pebbles' accretion led to the final spin far larger than the planetesimal theories [2]. A contemporary approach of pebble accretion will be utilized as a more recent framework, researchers established their simulations based on a series of three-dimensional dynamical equations formulated by Ida and Nakazawa, employing the Fehlberg method as a numerical method to solve the differential equations [3]. Their findings under numerical simulations are examined across 5 distinct regions. They modeled the simulation of interactions from protoplanets ranging from 10 to 3000 kilometer.

According to Ida and Nakazawa, for pebble accretion starting from a protoplanet sizing smaller than 200 km, the inward and outward accretion donate the opposite interactions onto the planet body, it is reasonable to abandon this regime since the total net contribution canceled to each other. As for protoplanet from 200 to 400 kilometers, the inside trajectory of pebbles and the exteriors have different interactions, the inner pebbles are having interactions and accretions ballistically. For the outer pebbles, they are engaged into trajectories finally comparing to the inner ones, pebbles from the exterior trajectory tilted orbits oppositely, contributing numerous prograde angular momenta to the spin. If protoplanets is modeled with size at roughly four hundred kilometers, pebble accumulation will finally tend to result the clockwise spin. Due to collisions occurring on the protoplanetary surfaces, the analysis suggests that tracks within the interior zone is transformed more steeply downward compared to the outer tracks. Consequently, prograde spin inhibits to the later planet, as the rocks of pebbles on the tracks strikes the planet vertically. For considering radii of one thousand kilometer, cross-section area of collision approaches to that of a half planetary Hill sphere (the dominated gravity zone of the planet itself), which enhances interior accretion by allowing pebbles captured for an extended duration. Conversely, the contribution of the exterior trajectory is diminished because the outer pebbles exhibit a greater downward velocity. The prograde interior accretion of pebbles leads to a spin direction that aligns with the prograde motion observed in the planets of ours system with sun. For increasing embryo radius up to three thousand kilometers, the Hill sphere increases significantly. As a result, the pebbles accreted from the outer band are drawn toward the planet by gravitational forces, contributing a counterclockwise spin. However, a substantial portion of the exterior pathway flows on an upward horseshoe path, ultimately resulting in a net retrograde spin, this result will be reversed again for larger radius because the increase of Hill sphere step by step contain all the pebbles to accrete and therefore create a prograde just as its orbit motion. In short, the sizes of protoplanets defines their Hill sphere to contain the small pebbles, the trajectory of dragging the pebbles into accretions is modeled from hundred kilometers to thousand kilometers with different final result. This idea of pebble accretion is further developed to fit the observation data of solar system planets. Our results for planets confirm the observed rotation periods of both the terrestrial planets Earth and Mars, as well as the ice giants Uranus and Neptune [1]. In terms of the observation, the pebble accretion theory does fit into the prograde motion of today solar system.

2.2. Stochastic accretion

On later stage of planet formation for planets like Earth, stochastic accretion involving larger rocky bodies may affect final angular momentum of Earth-liked planets, by comparison to the gradually built-up of other mass-accumulation. If a planet undergoes limited contribution from several contributors randomly, its obliquity should be zero degree with the invariant plane axis. In contrast, if a few large rocks accrete into the planet at different angles, it finally will have a distribution of obliquity and tilt randomly. Stochastic accretion determines the spin of terrestrial planets, even though pebble accretion theory has simulated the orbital periods of planets to match up with their present observed data [4]. Conversely, stochastic accretion theory is more compatible with the chemical composition of planet bodies. Instead of a process which build solely chondrites into planet, the accretion involving a limited number of rocky bodies may lead to a depletion of certain elements in the resulting planets. Typically, pebbles accumulate on Earth over time at approximately 1750 K, which is sufficient to melt them. However, the material heated to the gas state present inside atmosphere exists closely to the Hill radius and lower within the Bond radius, cooled to roughly four hundreds to one hundred in Kelvin. Consequently, these small pebbles solidate and canceled the element depletion, causing the pebble accretion does not match up perfect enough with the depletion pattern observed on Earth [5]. For planets like Earth, stochastic accretion is more favored for their final spin contributions. Dones and Tremaine in 1993 had built a model for stochastic accretion targeting at planets inside our solar system. starting the simulation from mass accumulations from uniform disks, Mars exhibits a standard rotation rate 1.5 far beyond the accretional case in order, which is suggested to locate between -2.2 and 0.3. This suggests that Mars has experienced stochastic accretion. Furthermore, the result modeled for Earth is approximately 1.1, which also falls outside the range of ordered zone. Additionally, due to the atmospheric effect on Venus and the tidal forces drugging the innermost Mercury, both Venus and Mercury may also undergo accretion stochastically. [4]. In conclusion, the stochastic accretion not only consider the chemical composition of the planets but also fit into the terrestrial planets of our solar system.

3. Contributor other than accretions

3.1. Giant impact from large rocky bodies

During the planetary formation process, the initial phase involves the interaction of gases and dust to form an initial disk, leading to the formation of kilometer-sized planetesimals. Such planetesimals may formed into an embryo of planet and start its accretion. In these development, huge rocks may directly hit onto the planet early or later in accretions and contribute tremendously to final angular momentum. For modelling under a uniformly distributed disk condition, accretions of masses do not provide the enough rotations for planets like Earth and Mars [6]. Usually, the final spin dynamic from a planet is calculated under the combining influence of the latest collisions in contrast to solely including a largest impact [7]. Agnor's approach employs N-body simulations with embryo masses equivalent to 0.04 times that of Earth, wherein embryo collisions are analyzed across a spectrum of embryo masses. The scattering events exert a more pronounced influence on smaller bodies than on their larger counterparts, leading to a broader distribution of higher eccentricities among the bigger embryos. Evolutional dynamic characteristics of these interacting events, either on the rotational elements and the orbital tracks, span a timeframe from 1 million to 40 million years. Regarding Earth, during the later stages in planetary formation, a sum of angular momenta including the result from a giant impactor must either exceed or at least match the current value to facilitate the formation of the Earth-Moon system. Agnor's simulations indicate that a decrease of rotational rate from the final impactor can result in a maximum net reduction of 0.85 L where L represents the angular momentum in the combined system of Earth and Moon. Conversely, approximately forty percent of the included collisions showed a reduction in the rotational rate and spinning momenta, averaging roughly 0.1 L. Generally, series of most significant contributors to a planet's spin angular momentum are the largest impactors, from their huge momentum originated from large masses. The first and the second largest impacts transfer averagely of thirty percents and nineteen percents of the final built-up mass respectively [7]. The most significant impactor contributes to the planetary angular momentum with averagely 1.44 L, while momenta distributions from giant impactors ranges uniformly to 3 times of the total momenta of moon and Earth. By contrast, the second strongest impact yields a reduced donation, averaging 0.67 L. Additionally, the final impact in this sequence accounts for approximately 8.3 percentage of the total planetary mass, accompanied by a magnitude of 0.76 L averagely. The model's findings for Earth and the Moon suggest that it is potentially viable to transfer the enough angular momentum to Earth-Moon system at present days since the summation of ranges of the previous impacting donation perfectly contain the total momenta with 1 L. Regarding terrestrial planets, those in the growth phase typically exhibit rapid rotation during the later stages. In the simulated final planets, those that underwent impacts similar to moon formation display the possible angular momenta options ranging between 0.2 L and 3.1 L. Agnor’s model states that colossal collisions involving planetary embryos can alters angular momentum of the planet largely, thereby profoundly influencing the ultimate spin of planets. Furthermore, during the concluding phase of planetary formation, these massive rocks can also involve in giving material to the developing planet mass.

3.2. Another simulation of giant impact

Standing on the model of Agnor, in 2007, Kokubo and Ida conducted a recent simulation that provided more comprehensive results regarding giant impacts. When simulating collisions involving 50 Earth-sized planets, the resultant spin angular momentum attributed to the final impactors is approximately 2.5 L. The data indicates a trend where the rotational momenta increase in relation to the planetary masses, with the highest mass, reaching up to twice of that of our Earth, yielding over 10 L in the simulation conducted by Kokubo and Ida. It seems that masses and rotational momenta evidently disapply in a linearly correlated pattern. Consequently, within a framework of the giant impact theory, the velocity acquired post-impactor is not correlated with the planet's mass, as it is expressed as the angular momentum of the planet over the moment of inertia of this planet cancelling the mass part after all. It is observed that the spinning velocity from planets in size like Earth tends to cluster roughly to a critical value, ranging from 1 to 7 with a unit of one divided by one hour. Additionally, the magnitude of the obliquity from planets varies between 0 degrees and 180 degrees, indicating that both clockwise and counterclockwise spinning direction both exist their feasibilities.

The result indicates that prograde spin with small obliquity, which is common to terrestrial planets in the solar system except for Venus, is not a common feature for planets assembled by giant impacts [8]. Consequently, while these giant impacts models offers enough rotational momenta for a potential future development of either a system combined with planet and it satellites or one solely planet itself, numerous terrestrial planets exhibit a significantly lower obliquity than what the model anticipates, which predict the obliquity to be uniformly and isotopically spread across the range of 0 degrees to 180 degrees.

3.3. Discussion

In term of the whole picture of planetary formation, Giant planets from the Doppler system have different features comparing to the small planet in the Keplerian system just like our Earth, several common characteristics of the smaller planets that have been discussed in the article are their low eccentricities which smaller than 0.1 and the small mutual inclination with orbits aligned within a few degrees. From these final results presents by smaller planets, it is convincing that these terrestrial planets will finally have a planet formation theory that can accurately predict or trace back their orbital dynamics and spins. However, modelling the development from a protoplanetary embryo to a final planet is still complex research involving in different mechanism. For example, the geometric process and interaction with the host star may also leave a change for the spin of planets. In addition, Research indicates that gravitational tides significantly influence the evolution of celestial bodies, particularly when they begin with a rapid rotation. Nevertheless, as the planet transitions into a slower rotation phase, the friction between the core and mantle becomes the primary factor governing the final changes in obliquity [9]. For the planet formation theory, the difference between the observed data of today planetary spin and the predicted value from either accretion process as well as the giant impactors does not evidently conclude the failure of these theories because of the long-term influence from solar tides or the planetary inner evolutions.

4. Conclusion

The previous paragraphs have discussed different planet formation theories that may bring angular momentum to the planet as well as comparing their predicted results with more favored situation in each case. To sum up, the process of pebble accretion typically provides the planet with its initial angular momentum and spin direction, which is influenced by the size of the embryonic body, it predicts well in the period and direction of rotation in some observation data. In certain instances, planets like Earth may also experience stochastic accretion. This method allows larger bodies to donate momentum causing significant obliquity and sufficient angular momenta to substantial planets. Furthermore, the giant impact hypothesis is regarded to be another donator in the development of planetary spin. In contrast to stochastic model, this model contributes to a more uniform distribution of the spinning axis and introduces considerable momenta to accelerate of decelerate the spins of planets. Still, the simulation using the N-body method is still relatively rough compared to what it should be during the formation of planets. In the case of the origin of angular momentum, a more universal and accurate model can be built in order to conduct a whole-picture simulation over the planet's bodies with different masses and their initial conditions.

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