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Mystery of the Moon's Origin

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MYSTERY OF THE MOON'S ORIGIN

by

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Dedication

Mom and Dad – thanks for always supporting me.

To my family and friends and all those who put up with me.

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Abstract

The dominant theory of the moon's origin is the Giant Impact Hypothesis, which states that the moon formed when a Mars-sized object - named Theia - impacted the proto-Earth early in the solar system's formation, with the resulting material contributing to the formation of the Moon. Using models of planetary development and the solar system's formation, we attempt to answer where the impactor - Theia - might have originated from. We conclude that the Asteroid belt is a likely location for Theia's formation, and we find that the parameters associated with this point of origin may help advance other models of the Moon's formation.

1. Introduction

As stated, the Giant Impact Hypothesis - postulating that the Moon was formed from the results of an impact between the proto-Earth and a Mars-sized impactor - is the most widely accepted theory of the Moon's formation (Robin M. Canup, 2004). However, there is an important, and as of yet not satisfactorily answered, question: Where did such a Mars-sized object come from? Where did it form? What were the dynamics that led to its impact with the proto-Earth?

Belbruno, Edward, & Richard Gott (2005) postulated that the Impactor formed in the Lagrange point, in the orbit around Earth, and then subsequently moved out of its position. However, Canup (2012) found that such a setup was unlikely. Since then, numerous simulations have been run modeling the ejection of various planet-sized objects in the Early solar system (Jacobson et al., 2014), (R. M. Canup, Barr, & Crawford, 2013); however, while some have made assumptions regarding an impactor origin, none have specifically identified the locations such an impactor formed, nor have they identified the characteristics surrounding the formation of such an object. This information is vital, because it illuminates the Impactor size, velocity, and other characteristics that can possibly shed light on some of the more vexing questions surrounding the moon's formation.

Additionally, some of the more nearby locations that the proto-Moon could have been sourced suffer from various problems. The impact that produced the moon is estimated to have occurred anywhere from ~ 29 Myr to ~ 130 Myr after the runaway accretion of the proto-Earth was completed (Yu & Jacobsen, 2011)(Jacobson et al., 2014). Forming in the same orbit as Mercury or Venus introduces a large, massive object sharing the same orbit, which would have produced eccentricities visible in the orbits of those planets. Additionally, there there would be the question of the ejection of the Impactor from those orbits, and such an ejection's additional effect on the planets' angular momentum.

Alternatively, if the Impactor were to have formed in the same orbit as the proto-Earth, this means that a Mars-sized object was at the same radial distance from the Sun as the proto-Earth, orbiting with an eccentricity (that led to its ultimate impact) for millions of years. How did they not collide? Or, as (Belbruno et al., 2005) said, "It is also hard to imagine an object as large as Mars forming in an eccentric Earth-crossing orbit."

Multiple, mutually exclusive theories have been proposed regarding the characteristics of such an impact. For example, although the generally regarded Giant Impact Hypothesis postulates a Mars-sized impactor (R. M. Canup et al., 2013), recent research has put forth impactors smaller than Mars (Robin M. Canup & Erik, 2001), to impactors five times the size of Mars (R. M. Canup, 2012).

Other details vary just as widely. (Robin M. Canup, 2004) postulated the Moon primarily formed from the impactor material, limiting the impactors most likely location. However, (Pahlevan, Kaveh, & Stevenson, 2007) found the Moon could have formed from the mixing of the material of both the proto-moon and the proto-Earth, allowing the proto-Moon to have formed from material isotopically different from the proto-Earth - and therefore outside of 1 AU (the assumed distance the proto-Moon would need to form to be isotopically similar). Salmon, Julien, & Canup (2012) found the Moon formed from an impact with one object, but Agnor (1999) simulated the formation of the Moon from impacts with multiple objects.

Early simulations were constrained by the idea that the Earth-Moon's angular momentum had to have been within limited boundaries (Cameron, 2001), but more recently Ćuk & Stewart (2012) found that the early Earth-Moon system's angular momentum could have been significantly higher initially (widening the possibilities surrounding the initial impact). Other simulations have shown that the Earth's angular momentum could have been impacted by collisions with multiple objects (Agnor, 1999).

Additionally, Reufer, Andreas, Meier, Willy, & Rainer (2012) found that an impact with a smaller, high velocity object was possible. More importantly, the investigation showed that such a high velocity impact would result in better combination of materials, and would accurately explain the current isotopic contents of the Moon and Earth. This would allow an impactor to originate anywhere, for the final combination of isotopes would be a mixture of both bodies. Furthermore, such a small, high velocity object would have different characteristics surrounding its origin than a low velocity, large object.

A better understanding of the proto-Moon's origins could narrow the possibilities, and better illuminate the characteristics of such an impact.

2. Theoretical Framework

The Giant Impact Hypothesis includes a number of unique characteristics that must be taken into account by any theoretical framework. First, the impact didn’t result in the complete combination of the material of both bodies, but instead resulted in the two body system of the Earth and Moon that we see today, with a relatively low mass ratio between the Earth and Moon. This is different than what is expected of most planet forming impacts.

Second, the impact is hypothesized to have occurred ~ 29 Myr - 139 Myr after the formation of the proto-Earth (Yu & Jacobsen, 2011; Jacobson et al., 2014); this is important, for the formation of the bulk of the inner planets’ mass is hypothesized to occur during “runaway growth,” with Earth’s formation estimated at ~ 11 Myr (Yu & Jacobsen, 2011). This puts the Giant Impact outside of the range of runaway growth, again reinforcing the difference between the Giant Impact and other ‘normal’ planet-forming impacts.

Most impact theories, regardless of their characteristics, require that a planetesimal formed someplace outside of the proto-Earth’s immediate orbit, and that planetesimal impacted the proto-Earth.

These two simple suppositions inherently produce three limiting circumstances: 1), Any planet-sized object must have formed within a stable location, over a period of years long enough to produce an appropriately sized object; 2), circumstances must have driven that object to impact the proto-Earth; 3) Such events occurred within a generally defined timeframe.

3. Asteroid Belt

The asteroid belt provides an interesting candidate for the possible source location of the proto-Moon. It can provide the mass, the stable location for formation, and a method of ejection. Additionally, such a planetary body forming in the asteroid belt could possibly also assist other theoretical investigations of the Moon and asteroid belt - such as the mixing of the Lunar Impactor's matter with that of the proto-Earth, or the loss of mass of the asteroid belt.

What are the constraints regarding the formation of the proto-Moon in the Asteroid belt? First, there must be enough time for an object the size of Mars - or smaller, see below - to have formed. Terrestrial planetary formation occurred in three phases; however, at the second phase - the runaway growth phase - we see the development of planetary objects up to Mars-sized in ~ 10 Myr (Jacobson et al., 2014). Assuming that such an object (in the asteroid belt) formed concurrently to the remaining terrestrial planets, then the timeline of such an object's development should be similar.

Additionally, an object that is less massive than a Mars-sized object - which fits a number of other constraints, and can arguably be a better fit for the Asteroid belt as a source (because a smaller object at a high velocity will be less likely to obliterate the proto-Earth upon impact) -

would not need as long to develop, and could have formed in the earlier, planetary embryo phase.

Secondly, there needs to be a method of the planetary bodies' ejection from the asteroid belt. Third, there is the question of the timeline of events - does the ejection of a lunar impactor originating in the Asteroid belt fit the known timeline of events in our solar system? Lastly, there is the question of how this idea would impact other theories of the Moon's formation.

4. Support

One reason why the asteroid belt provides an interesting candidate for the possible source location of the proto-Moon is its abundant material in the early asteroid belt. The asteroid belt in its present form is missing over 99.9% of its mass, estimated to originally have been "several" Earth masses (Weidenschilling, 1977). As stated earlier, the most popular version of the Giant Impact hypothesis proposes an impactor of approximately the same mass as Mars, or ~ .10 present-day Earth masses. This means the early asteroid belt had many times as much mass as required to form the Impactor.

Accepted models of the Solar System's formation (Morbidelli, Lunine, O'Brien, Raymond, & Walsh, 2012) have the planets accreting in three stages. The first stage produces planetesimals, the second stage - the runaway growth stage - produces planetary embryos, and the final (and longest) stage producing the planet sized objects that we know. While the exact timelines of each stage are contested, two things are agreed upon: First, that the first two stages of planetary growth - transforming dust to planetesimals, and then such planetesimals into planetary ‘embryos’ of approximately Lunar to Mars-sized in mass - occur concurrently and equally for the gas giants as well as for the terrestrial planets. It’s only after this second stage (post ‘runaway growth’) that the gas giants’ growth takes off more rapidly than the terrestrial planets. This means that planetary objects Lunar or Mars size had time to develop in the asteroid belt prior to Jupiter growing massive enough to disrupt their growth (Chambers & Wetherill, 1998; Walsh et al., 2012).

A more detailed breakdown has the first ~ 4 - 5 Myr producing Lunar to Mars-sized planetary objects, prior to the complete development of Jupiter (Walsh et al., 2012). A Mars-sized Impactor could have therefore formed in the asteroid belt in the same timeframe, assuming approximately the same rate of formation of the other terrestrial planets (Chambers & Wetherill, 1998).

Furthermore, it must be noted that these values are not set in stone. For example, the Frost Line (the distance from the Sun beyond which gases still remain frozen) was at a different location than it is currently - closer to the Sun and in the Asteroid Belt - during the Solar System’s formation (Lecar, Podolak, Sasselov, & Chiang, 2006). This means that a planet-sized object that may have formed in the Asteroid Belt would have formed quicker than the rest of the terrestrial planets due to the effects of significant ice in the accretion zone and that ice’s accelerating effect on planetary formation (Hubickyj, O, P, & J, 2005).

Other instances of variance include the possibility of a smaller than Mars-sized object. For example, an Impactor less massive than Mars impacting at a higher velocity could have resulted in much greater mixing of material between the proto-Moon and the proto-Earth, and would better explain the observed isotopic content of the Moon.

The question now becomes: how was an object of a mass similar to Mars ejected from the Asteroid Belt?

Jupiter's interaction with the Asteroid belt is the reason why a planet has not formed within the Belt, often due to being ejected after interactions with Jupiter's gravity (Rayman, Fraschetti, Raymond, & Russell, 2006). Multiple theories exist as to the exact mechanics of how the contents of the Asteroid Belt were ejected.

In general, there are two different categories of ejection. In the simplest version, Jupiter's gravity interacts with an object, and over time such an object's resonance with Jupiter can cause it to be ejected (Reufer et al., 2012). More exotic versions have Jupiter migrating inward towards the inner planets, and then migrating back outwards, scattering asteroids in the process (Walsh et al., 2012).

What is clear is two things: First, Jupiter's ample gravitational field interacts with the objects in the Asteroid Belt, and has ejected numerous such objects (Petit, 2001). Second, this interaction didn't start to happen until Jupiter coalesced into a planet of such size that its gravity was large enough to interfere with the formation of objects at the distance of the Asteroid Belt (Petit, 2001).

Additionally, the Impactor's ejection would depend on where it formed in the Asteroid Belt. Formation closer to Jupiter, and especially where Jupiter's gravitational field is in resonance with the Impactor, could lead to a quicker ejection, whereas if the Impactor formed away from Jupiter and out of resonance, it wouldn't be subject to ejection from resonance at all, and would instead need Jupiter's migration, or another cataclysmic gravitational interaction, for its ejection. Locations in between could lead to a variety of different outcomes.

Current theory surrounding the formation of the Jupiter has Jupiter forming relatively quickly, in a few Myr (Walsh et al., 2012), and before the terrestrial planets completely form. If Jupiter's gravitational field then began the resonant process with a planetary embryo that had formed in the Asteroid Belt (the future Impactor) it would need ~ 29 Myr - 120 Myr to knock such a planet out (based on the earlier timeline of the Impactor's collision with the proto-Earth). This fits the timeframe that simulations done on an Asteroid Belt populated with planets both smaller and larger than the proposed Mars-sized Impactor produced (Chambers & Wetherill, 2001).

5. Characteristics

An impact by an object from the Asteroid belt introduces a number of interesting variances in the characteristics of a Giant Impact between the proto-Earth and a proto-Moon.

First, and most importantly is the velocity of the impact. The proto-Moon would have been ejected from the Asteroid Belt, and therefore have traveled a significant distance before actually impacting with the proto-Earth. This means that the impactor would have gained velocity from the time of the ejection event, until the actual impact. What was the velocity of the two bodies at impact? This depends on direction of the proto-Earth's motion and the direction of the Impactor's motion, relative to each other.

If, for example, both objects were moving directly towards each other, then the velocity of their impacts would be the sum of their individual velocities. This would be the maximum velocity circumstance. The minimum velocity circumstance would then be the opposite - with the Impactor making contact with the proto-Earth as the proto-Earth is receding away (in its orbit). This separation between the velocities is wide, and therefore allows for a wide variety of possible impact scenarios.

An impactor coming in at a very high velocity would need to be significantly less massive than an impactor coming in at a lower velocity, to produce the observed results. In between there are also a variety of possibilities.

The moon Impact theory that seems to most fit with the notion of a proto-Moon originating in the Asteroid Belt is the High Velocity impact theory that supposes an impact between an object of lower mass, but at a higher velocity. While there are a myriad of different theories as to the origin of the Moon, this particular one has the advantage of better explaining the peculiar connection between the isotopic characteristics of the Moon and that of the Earth. Such a high velocity impact produces significant mixing of the material from the two bodies, and results in a in an isotopic configuration in both bodies congruent with observation (Reufer, Andreas, Meier, Willy, & Rainer, 2012).

We encourage others to look into the possibility of the proto-Moon originating in the Asteroid Belt, and the impact this would have.

6. Conclusions

In this paper we asked the question - "Where did the proto-Moon originate from?" We found that there are unanswered problems with some of the possible locations of the proto-Moon's formation. We introduced the idea that the Impactor formed in the Asteroid belt, and was ejected due to interactions with Jupiter. We also provided some parameters surrounding the location of formation of the Impactor, and tried to eliminate some possibilities. Additionally, we found that a Lunar Impactor originating in the Asteroid Belt is consistent with some other Impact and Asteroid Belt simulations. Finally, we found some interesting consequences of the proto-Moon forming in the Asteroid Belt, and highlighted related areas of research.

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Vita

Abubakr Hassan was born in [redacted] 1978, in [redacted], California. He was home schooled, ultimately earning his diploma [redacted] in [redacted], Michigan.

Abubakr Hassan is pursuing two Bachelors of Science degrees - in Astrophysics and Computer Science - at the University of North Florida. Also at the University of North Florida, Abubakr is a member of the Phi Kappa Phi Honor Honor Society, the UNF Honors Program, and is the founder of the UNF Institute of Innovation. Abubakr was awarded the Presidential Scholarship, as well as other financial awards. In addition to his studies, Abubakr is very involved in various student activities and clubs, including working closely with the UNF Interfaith Center, as well as being the president of The UNF Muslim Students Association, and the UNF Political Science Club. Abubakr Hassan plans to pursue a PHD in Astrophysics, a masters in Computer Science, and start his own software company.