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THE PROPOSED ORIGIN OF OUR SOLAR SYSTEM WITH PLANET MIGRATION

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ABSTRACT

Two new models to explain the origin and history of our solar system are reviewed from a creation perspective, the Grand Tack model and the Nice model. These new theories propose that the four outer planets formed closer to the Sun, as well as closer together, than today. Then their orbits underwent periods of migration. Theories developed in the research on extrasolar planet systems are today being applied to our own solar system. The new migration models are finding much support from the planetary science community. These new models are summarized and evaluated Biblically and scientifically. Rather than demonstrating how our solar system formed, the new migration models can be understood as supporting the intelligent design of our solar system.

KEY WORDS

solar system, migration, Grand Tack, Nice Model, planets

INTRODUCTION

For many years the accepted theory for the origin of our solar system has been what is referred to as the Nebular Hypothesis, in which a nebula collapses into a disk from which our Sun and planets form. In the 1994 Proceedings of the International Conference on Creationism (ICC) the author critiqued this theory (Spencer 1994). After 1994 came a great deal of scientific research from astronomers regarding extrasolar planets (exoplanets). The extrasolar planetary systems are generally found to be quite different than our own solar system and this has led to new planet origins models being put forward to explain the origin of the extrasolar planetary systems. The author has addressed the evidence for extrasolar planets, the origin of extrasolar planets, and other origins issues regarding our own solar system in various papers since 1994 (Spencer 2001, 2007, 2008, 2010, 2014a, 2014b). Extrasolar planet systems demanded a different approach from earlier scientific models of planetary systems, mainly because many of the exoplanet systems were found to have planets present very near their stars. This motivated the development of theories on planet orbit migration. Today these planet orbit migration models are being applied to the origin of our own solar system. Thus since 2005 two new models have been developed regarding the formation and history of the planets in our own solar system, called the "Grand Tack" and the "Nice" model. ("Nice" is a reference to the city in France, where scientists first met to develop the model.) The Grand Tack model pertains to the inner solar system and has Jupiter and Saturn migrating first inward and then outward. The Nice model holds that Jupiter, Saturn, Uranus, and Neptune initially formed nearer to each other and closer to the Sun, then migrated outward to their present orbits. This paper will do a review of these new models and update the topic of the origin of our solar system from a young age creation perspective.

In 1994 the author pointed out scientific difficulties with secular naturalistic theories on the formation of our solar system and advantages of a young age creation perspective. The Bible implies that Earth was created supernaturally with a special purpose of being inhabited by humans. The creation account in Genesis chapter one is clearly supernaturalistic and thus rules out many naturalistic formation theories. The creation account does not explicitly describe the creation of many objects in our solar system. However, it does mention the Sun and Moon being created on the fourth day. Thus, it seems reasonable to infer that all other objects in our solar system were formed on the fourth day in the creation week. The creation week was a unique time in which special processes were at work not like normal natural processes. Then God's special creative activity completed on the sixth day of the creation week.

Since 1994 the author's views have changed somewhat on certain scientific issues. The author's former emphasis on a solar system catastrophe was considered mainly in connection with evidence for cratering across our solar system. This stimulated debate among creationists regarding impacts in the solar system and impacts from space during Noah's Flood. At the present time, the author leans more toward the role of the creation week processes and less on catastrophic events for explaining the solar system. The Fourth Day Impacts Hypothesis of Faulkner (2014) seems to the author to be the best explanation of cratering in the solar system. However, this does not mean the concept of impacts during the Noahic Flood has been abandoned by the author, just that the Flood involved fewer impacts. Also, the impacts which happened during creation week did not affect Earth.

The accepted naturalistic theory on the origin of our solar system was described by Spencer in 1994 as the "Modified Nebular Hypothesis" (p.514). The early stages of the Nebular Hypothesis regarding the collapse of a nebula in space to a spinning disk is envisioned today as much the same process as in Spencer 1994 (p. 514-518). After the collapse of the nebula into a disk the central mass becomes a star with nuclear fusion operating. At this stage, the star is surrounded by a spinning disk of gas and dust from which planets (and other objects) may form. The mass of the gas is thought to be possibly a hundred times the mass of the dust initially. This stage with the Sun operating as a star surrounded by a disk of

gas and dust may be considered time zero for planet formation. The new planet migration models for our solar system begin with the formation of Jupiter within the first 10 million years. The disk around the star is referred to as the "protoplanetary disk," "protosolar disk," or sometimes as the "solar disk." It is referred to sometimes as the "solar disk" because it is believed to initially be of the same overall composition as the Sun. The distribution of material in the disk as well its density is a critical issue for planet formation theories. The new Grand Tack model begins with the formation of Jupiter and deals with Jupiter and Saturn migrating inward toward the Sun, then Jupiter and Saturn enter a resonance and reverse their migration (Walsh, et. al., 2011, Walsh, et. al., 2012, Jacobson and Morbidelli, 2014, Isidoro, et. al., 2015). Thus, the Grand Tack has Jupiter and Saturn migrating first inward then outward. Then the end of the Grand Tack scenario becomes the beginning of the Nice model. The Nice model then proposed that Saturn, Neptune, and Uranus migrate outward to their present orbital positions over a period of 100 million years (Tsiganis, et. al., 2005, Levison, et. al., 2008, Batygin and Brown, 2010). These new models have generated great interest and enthusiasm among planetary scientists because of the apparent success from them in producing the characteristics of our solar system in computer simulations.

This paper will do a review of the new migration theories for the formation of our solar system. In what follows, theoretical methods used in planetary science today will be summarized followed by an explanation of the new Grand Tack and Nice models for our solar system. Following this will be the author's interpretation and evaluation of the Grand Tack and Nice models in the Discussion section. Lastly in the conclusions will be comments on the significance of this research to creationism.

THEORETICAL METHODS IN PLANETARY SCIENCE

1. Accretion of Solid Bodies

Planet formation theories have been developed that depend critically on the formation of sizable solid objects known as "planetesimals" and "planetary embryos." The protoplanetary disk is initially composed of gas and dust. The dust is thought to become more concentrated from settling to the midplane and possibly from its tendency to spiral inward. Experiments have demonstrated that very small dust particles can stick together in collisions (Poppe, Blum, Henning, 2000 and Blum, et. al. 2006). Theories assume that agglomerated dust can eventually grow into larger solid objects on the order of 1 km in size and larger. These are the planetesimals. Planetesimals in turn grow through collisions and collecting material near them until some of the planetesimals grow to larger sizes from approximately 1000 km diameter to the size and mass of Mars. These are the planetary embryos. It is thought that the protoplanetary disk in the early solar system likely contained perhaps a few dozen planetary embryos, of which only a few survived to the present.

It is believed growth of the largest gas giant planets would have been most rapid at the start, while gas is most readily available in the disk. Gas giant planets are believed to grow initially by a process called core-accretion (Matsuo, et. al., 2007) and later by absorbing planetesimals. In core-accretion, solid planetesimals and other material must combine to make a mass thought to be of a minimum of approximately 4 Earth masses (m_E). If this takes place quickly enough so that the gas in the disk is plentiful, the planet core can attract gas to it and it can grow rapidly until gas becomes depleted in the disk. If the planet core does not grow to about 4 m_E in a sufficiently short time, then this will limit its size because of the dissipation of gas in the disk. In the first few million years of the disk, growth of planetary embryos is thought to be more rapid. The process of absorbing solid planetesimals is believed to form the terrestrial (rocky) planets. Zahnle, et. al. (2007, pp. 41-42) summarized the early stages of planetary accretion of the rocky planets as follows:

> In the simplest terms accretion of terrestrial planets is envisaged as taking place in four stages:
> (1) Settling of circumstellar dust to the mid-plane of the disk.
> (2) Growth of planetesimals up to ~1 km in size.
> (3) Runaway growth of planetary embryos up to ~10^3 km in size.
> (4) Oligarchic growth of larger objects through late-stage collisions.
>
> Stage 1 takes place over time scales of thousands of years and provides a relatively dense plane of material from which the planets can grow. The second stage is the most poorly understood at present but is necessary in order to build objects that are of sufficient mass for gravity to play a major role. Planetesimals would need to be about a kilometer in size in order for the gravitationally driven stage 3 to start.
>
> We do not know how stage 2 happens, although clearly it must. Scientists have succeeded in making fluffy aggregates from dust, but these are all less than a cm in size.

Planetary scientists commonly refer to objects larger than 1000 km as planet embryos. Thus, our Moon, whose diameter is 3,476 km, could be referred to as a planetary embryo. The rate of growth of the solid planetary embryos is thought to depend chiefly on their relative velocities in collisions and the relative numbers and masses of the embryos compared to the planetesimals. When the planetesimals are very numerous they tend to reduce the velocities of the embryos and the slower speeds of the embryos facilitates faster accretion. This is Stage 3 referred to above as "Runaway growth." In this stage the planetary embryos are thought to grow relatively rapidly. In Stage 4, oligarchic growth, the number of planetesimals is not enough to affect the velocity of the embryos and the embryos are larger. Thus, in the oligarchic growth stage the gravity of the planetary embryos draws planetesimals to them.

2. Starting Assumptions of Current Theories

Several overarching assumptions are made in current theories regarding the overall process of how the protosolar disk evolved into the current array of planets and small bodies in our solar system. First, the protosolar disk is initially assumed to contain sufficient material to form the planets and other objects in our solar system. Early work on modeling the protosolar disk was done from the late 1960's through the mid-1980's. Two significant papers on what has been called the Minimum Mass Solar Nebula

(MMSN) were by Weidenschilling (1977) and Hayashi (1981). The protosolar disk theory in these early models has not been modified very significantly until very recent years. Some recent revisions of these disk models will be discussed below. The general concept is to derive a mathematical representation describing how the density of the disk would vary as a function of distance from the Sun. The density is determined by estimating a "feeding zone" in the vicinity of each planet based on their current positions. The planets are assumed to have accreted in their present locations with no migration in these disk models. These models also assume that all the solids in the vicinity of each planet accreted onto the planet. Hayashi (1981) indicates the initial mass of the protosolar disk is in the range of 0.01 – 0.04 times the mass of the Sun (p.114).

Solar system origins theories from the 1980's thought of planet formation of the inner and outer planets to be essentially concurrent but that the inner planets formed more slowly due to the higher temperatures at their orbital positions. However, today in the light of the new Grand Tack and Nice Models the gas giant planets in the outer solar system form first and the inner planets form later. Today the outer planets would be understood to reach most of their current mass within 10 million years but then continue to accrete material at a slower rate for perhaps 100 million years or more. The inner planets do not accrete large gas concentrations early but they grow by the oligarchic process described above from impacts of planetesimals and collisions with planetary embryos. Volatile elements and compounds in the inner planets, including water, are believed to be delivered to the growing inner planets primarily from planetesimal impacts. The "end" of planet formation is generally taken to be the end of the Late Heavy Bombardment and the proposed impact that is thought to have formed our Moon. The timing of the Moon-forming impact is debated but it is taken as sometime from approximately 30 to 120 million years after the beginning of the formation of Earth.

Today the research on extrasolar planets has convinced many scientists that our solar system could have lost planets and that the current planets may not be in the same orbits in which they formed. There have been some observations of so-called "rogue" or "free-floating" exoplanets using infrared telescopes (Liu, 2013) or gravitational microlensing (Clanton and Gaudi, 2016). There are some uncertainties regarding these objects and there is some on-going debate over whether they should be viewed as planets or as small dwarf stars. The apparent existence of planets separated from their stars has led to planetary scientists proposing that the planet formation process can involve planet orbit migration and planet-planet scattering events that can sometimes eject planets away from their stars. Simulations do sometimes show planets being ejected. Thus, planet formation is viewed as a process in which some planets survive and some do not.

3. Planetary Migration

Planet orbit migration is now a well-accepted process that is thought to have happened in many extrasolar planetary systems as well as in our own solar system. Today extrasolar planets are detected by radial velocity redshift measurements, by transits of their star, by direct infrared imaging, and by other methods (Spencer, 2011, 2017). Planetary migration is a theoretical concept that is thought to explain the origin of planetary systems. In many observed extrasolar planetary systems there are planets quite close to the star, which places them at temperatures where it would be impossible for gases to condense. Thus, it was proposed that these "hot Jupiter" planets actually formed farther from the star where temperatures would allow gases to condense onto the planet, then as the planet formed or perhaps later from other events, it migrated inward toward the star. Note that this migration is assumed, not observed. To date, no researchers have claimed to have direct observational evidence of migrating exoplanets. Not all extrasolar planets are "hot Jupiters" near their star. Extrasolar planetary systems are known to have a variety of orbital configurations. It is understood that planet migration can be either inward or outward depending on the conditions in the system being studied. Planet migration theories have been developed through many theoretical studies. Planet migration is believed to have multiple possible physical mechanisms which can be theoretically compared considering their causes:

- Caused by the disk of gas and dust (migration Types I, II, or III)
- Caused by solid planetesimals in the system
- Caused by planet-planet gravitational interactions and orbit resonances

Migration caused by the protosolar disk involves an interaction between the disk and a forming planet. This encompasses at least three modes of migration referred to in the scientific literature as Types I, II, and III. These three migration modes have been applied in models of our solar system. There are certain prerequisites to these migration processes to be possible. First, these modes of migration all require a planet to be of at least several Earth masses while gases have not dissipated in the disk. The distance scales where the models are applicable depends on the star and the characteristics of the disk. Torques are produced on the planetary embryo by gases that stream past it moving near the planet. Gases just inside or just outside the planet's orbital position enter what are known as Lindblad resonances with the orbiting planet that lead to a tidal interaction with the planet. Streamlines of gas can come to follow what are called horseshoe streamlines that exert a torque tangential to the orbit of the planet.

These modes of migration are distinguished by the relative mass of the planet in comparison to the mass of the disk, and the rate of orbit migration. In Type I migration the disk is massive and dense enough that the presence of the planet has little effect on the distribution of gas. Thus, Type I migration tends to be more applicable in earlier stages when the disk has not dissipated and the planet is well below its final mass. In Type II migration the planet is larger and the disk material is significantly affected by the presence of the planet. Normally this means that a gap forms in the disk in the vicinity of the planet's orbit. The planet clears away a zone on either side but a density wave forms in the disk such that a stream of gas forms that passes by the planet. Type II migration can be considered a slow gradual type of change in the orbit. Type I migration is more rapid than Type II. It is believed that a planetary system can undergo a transition from Type I to Type II as a planet grows and as the disk changes. This transition can be important for explaining how the migration process can stop and allow the planet or planets to not spiral into the star. Type III migration is another mode that is sometimes described as "runaway" migration.

Theory from various researchers may not be in complete agreement regarding the applicability of this mode of migration. Usually the scenario for Type III migration is described as being after Type II migration has taken place and a gap has set up in the disk. Gases can move across the gap and cause an accelerating migration of the planet. Though Type III migration can be either inward or outward, it is usually inward toward the star in simulations. Type III migration requires a more massive disk. If Type III migration is possible it often implies the planets will spiral into the star, but it depends on how the model is applied. Migration Types I, II, and III have all been applied in modern theories of the formation and evolution of our solar system (Goldreich and Tremaine, 1980, Papaloizou, et. al. 2007, Fog and Nelson, 2007, Hasegawah and Ida, 2013).

Another form of migration considered theoretically possible is where solid planetesimals cause the planet orbit to change (Levison, et. al. 2007). This requires that there be enough planetesimals that their collective mass is comparable to multiple additional planets. Planetesimals can be scattered by the planets as they pass near them. Each time a planetesimal has its orbit altered by a planet, it transfers a small amount of its orbital angular momentum to the planet. This is the primary mechanism of planetesimals causing planet migration. Thus, it requires a large number of planetesimals to cause a significant sustained effect on a planet's orbit. Planetesimals can also cause a planet's orbit to round so that it is less eccentric, if there is a sufficient number of objects near the planet's orbit. This process is referred to as dynamical friction. Planetesimals can continue having an effect on the orbits of planets after gases have dissipated in the disk. Thus, planetesimals are understood as being able to exert a slow effect that changes planet orbits over tens to hundreds of millions of years.

The third type of planetary migration mechanism is from planet-planet interactions and orbit resonances. In a system of multiple planets which may be migrating, the planets may migrate at different rates due to their varying masses and may come into orbit resonances (Morbidelli, et. al. 2007). Orbit resonance refers to conditions where two or more objects have orbital periods which are small integer multiples of another orbiting body. Resonances can alter orbits over time because the two objects in resonance come nearer to each other in a repeating manner as they complete many orbits. Determining if two planets (or moons) are actually in a resonance requires good observations and analysis of their orbits. Sometimes apparent resonant motion can be explained as some type of temporary oscillation in the orbit. An orbit resonance may be a very stable configuration but it can also be a migration mode in which two or more planets migrate together. There are many known orbit resonances in our solar system but normally observed resonances are between a planet and smaller bodies such as moons, asteroids, or in some cases comets. If a massive body comes into resonance with a very small body, the small object's orbit can be dramatically altered by the massive body. In a similar manner, a large planet can have a significant effect on smaller planets that may come into resonance with it. Thus, gravity can "nudge" the two objects closer when they are at their closest relative positions. If planets have eccentric orbits, resonance tends to cause the orbit of the planet of the lower mass to become more eccentric. Thus, if one large planet is migrating and it is in a resonance with another planet, it may cause the smaller planet to migrate with it. If sufficient planetesimals are present and gas is still present in the disk, there could be a combined effect of all these mechanisms on planet orbit migration.

NEW SOLAR SYSTEM THEORIES

1. The Grand Tack Model

The Grand Tack model and the Nice model apply planet orbit migration theory to our own solar system. These new models are believed by some scientists to address many limitations and difficulties with solar system theories of the past. Because gas in a disk will dissipate in a few million years it is believed that large gaseous planets form first. This process is believed to have started without any planet migration but then as the forming planet gets larger the gas and other material in the disk may cause it to migrate (in Type I, II, or III migration above). The Grand Tack model begins with Jupiter having formed and nearly at its full mass and it begins to migrate inward toward the Sun. Initially Saturn accretes at a slower rate than Jupiter, and Uranus and Neptune accrete at rates slower than Saturn because the density of the disk trails off with distance from the Sun.

The Grand Tack scenario applies to the period after Jupiter has formed for a period of 600,000 years. In the Grand Tack scenario Jupiter is assumed to have initially formed at approximately 3.5 A.U. from the Sun. The Grand Tack addresses the inner solar system and defines a set of conditions where it is thought the four inner planets as well as the asteroid belt would form. The Nice model essentially starts where the Grand Tack ends and addresses the outer solar system, including the migration of Saturn, Uranus, and Neptune, and effects of this in the outer planetesimal belt. In the Grand Tack scenario Jupiter would begin migrating inward by either the Type I or Type II mechanism above, accreting some material as it goes. Saturn does not migrate until it nears its present mass and size. Then it begins to migrate faster than Jupiter and it catches up with Jupiter when Jupiter is at approximately 1.5 A.U. from the Sun. This distance is chosen to allow for the formation of Earth and Mars at approximately the right distances from the Sun and to allow for Mars forming with approximately the correct mass. In this approach, the mass of Mars is much less than that of Earth because Jupiter had scattered away much of the solid material in the zone from approximately 2 A.U. to 5 A.U.

Jupiter's movement in to 1.5 A.U. causes large planetesimals and planet embryos to be pulled inward with it. So, the result of Jupiter's inward migration is to form a belt with many of the largest planetesimals and a limited number of larger planet embryos in the region from approximately 0.3 to 1.0 A.U. from the Sun. There would be many collisions and interactions of objects in this inner planetesimal belt. Some planetesimals and planet embryos would fall into the Sun and some could be ejected from the solar system. But the collisions with planet embryos are believed to lead to a small number of surviving rocky planets. Thus Mercury, Venus, Earth, and Mars are believed to have formed from this inner belt of objects. Jupiter's movement inward also causes planetesimals that were in the region from 2 to 5 A.U. to move inward and they collide with the planet embryos forming in the inner belt. This provides volatile compounds such as water to Earth and the other

terrestrial planets.

By the time Jupiter migrates in to approximately 1.5 A.U., Saturn has migrated to a position near Jupiter and the two planets enter a 2:3 orbit resonance. In simulations entering this resonance changes the torques on Jupiter and causes Jupiter and Saturn to begin migrating outward. This reversing of the migration depends mainly on two conditions, a) the mass ratio of Jupiter to Saturn must be in the range of from 2 to 4 and b) the two gaps in the annular disk opened up by Jupiter and Saturn must overlap (Raymond and Morbidelli, 2014). The mass of Saturn determines much about how the inward migration occurs. If Saturn's mass is too large, it will migrate inward too rapidly and then it will not have an adequate braking action on Jupiter. If Saturn's mass is too small, it will migrate slower but it may not catch up with Jupiter and it may not be massive enough to stop Jupiter's inward migration. Thus, if Saturn's mass is either too large or too small, both Jupiter and Saturn would be likely to spiral into the Sun. After Jupiter and Saturn enter the 2:3 resonance they migrate outward essentially until the gas is largely dissipated from the disk. At the end of the Grand Tack Jupiter is slightly outside its current orbital position and Saturn, Uranus, and Neptune are well inside their current actual orbits (see Table 1). This configuration at the end is an intended result of the model in order to make it consistent with the Nice model scenario.

Table 1. The approximate orbital positions of the four outer planets at the end of the Grand Tack and Nice scenarios, compared to the current semi-major axis positions of the same planets. The Grand Tack ends after 600,000 years has elapsed in the simulations. Positions at the end of the Nice model migration are after up to 700 million years has elapsed. Variations on these numbers are possible from the simulations of various researchers.

PLANET	CURRENT POSITION (A.U.)	END OF GRAND TACK (A.U.)	END OF NICE (A.U.)
Earth	1.00	1.00	1.00
Mars	1.52	1.52	1.52
Jupiter	5.20	5.4	5.2
Saturn	9.58	7.1	8.8
Uranus	19.3	9.8	19.0
Neptune	30.2	12.8	26.0

In the Grand Tack, the region near the Sun is a densely packed zone where the terrestrial planets form over a period of up to 150 million years. In this near-Sun zone some planet embryos which may have formed early before Jupiter's inward migration could be destroyed. Thus, the terrestrial rocky planets do not really have opportunity to form until Jupiter begins its outward migration phase. The terrestrial planets grow by oligarchic growth. This is where the planet embryos are of much larger mass than the surrounding planetesimals. The planetesimals are drawn to the embryos by gravity and are also swept up by the embryos in their orbits. Embryos also undergo collisions with each other. Simulations typically assume that every collision with a planet embryo results in the merging of the objects, regardless of whether the "impactor" is another embryo or a planetesimal. In the early solar system while Saturn is still growing the "snow line" would be located at approximately 3 A.U. from the Sun. Today this point would be at approximately 5 A.U. distance from the Sun. This is the distance at which water ice could exist at an equilibrium temperature below freezing and not evaporate. When Jupiter migrates in to 1.5 A.U. it pulls planetesimals from the region beyond the snow line inward. Jupiter will also scatter planetesimals that formed in the near-Sun region outward. So, an important effect of Jupiter's inward and outward migrations is to mix small bodies in the solar system.

The current asteroid belt, located roughly from 2 to 3.5 A.U. is understood as having formed after Jupiter's outward migration. Though planetesimals (or asteroids) could have formed early before Jupiter's inward migration, those objects would have been scattered as a result of Jupiter and Saturn's migration episodes. The current asteroid belt has several characteristics that are difficult to explain in traditional no-migration models of the formation of the solar system. First, the asteroids have a range of orbit eccentricities and orbit inclinations that are unlike those of the planet orbits. Though many known asteroid orbits have eccentricities of roughly 0.2 or less, some go as high as 0.4 or more. Orbit inclinations of most of the asteroids are 20 degrees or less but some have orbits inclined up to 42 degrees in angle (Lewis, 2004, p. 70). The scattering associated with the migrations of Jupiter and Saturn are taken as supporting the Grand Tack because the planetesimals would be scattered into a variety of orbits. Secondly, the asteroid belt is somewhat "zoned by composition" and this is taken as support for the Grand Tack model as well (Walsh, et. al., 2012, pp.1943-1944). For example, of the various spectral classes of asteroids, Class S, consisting of metals and minerals such as olivine and pyroxene is most prevalent at a distance of about 2.5 A.U. But Class P asteroids have spectra indicating carbon and various organics and are most abundant at about 4 A.U. (Lewis, 2004, p.401). The Class S and Class P asteroids are both spread over a wide region but their regions overlap only slightly. Other classes of asteroids have their own characteristics and regions as well. Thirdly, the asteroid orbits strongly cluster around a number of orbit resonances with Jupiter. This is also taken as support for the Grand Tack, since Jupiter's migration is thought to be a natural explanation of this.

2. The Nice Model

The Nice model begins after the end of the Grand Tack and addresses several aspects of the outer solar system. Traditional solar system theories without planet orbit migration have had some difficulties addressing certain questions that are addressed in the Nice model. The Nice model addresses the following: 1) how the outer planets came to their present orbits, 2) how the Trojan asteroids in the outer solar system came into their orbital configurations, and 3) The Nice model also suggests that the migration of the outer planets caused an instability among small bodies that caused the Late Heavy Bombardment, generating many impacts throughout the solar system.

To understand how the Nice model addresses the above issues, we must consider the scenario it proposes. The Nice model begins with Jupiter located at approximately 5.45 A.U. from the Sun (slightly outside its current position). The four outer planets, Jupiter, Saturn, Uranus, and Neptune begin the Nice scenario much nearer to each other than their current orbital configurations. The

orbital distances from the Sun of Jupiter and Saturn at the start of the Nice scenario is quite important. Saturn begins the Nice model at approximately 8.5 A.U., which places it just inside the 1:2 Jupiter-Saturn resonance. Saturn migrates outward and passes through the 1:2 resonance. In most simulations of the Nice model, Neptune begins the Nice scenario nearer to the Sun than Uranus. Neptune and Uranus have strong interactions with Saturn via resonance as well. Neptune and Uranus begin the Nice model in the distance range of 11 to 17 A.U. from the Sun. Neptune and Uranus migrate outward due resonances with Saturn and due to the influence of a massive belt of rocky objects in the region from about 15 to 35 A.U. from the Sun. Neptune and Uranus undergo a period of rapid migration outward and are believed to have likely exchanged positions multiple times until they came to a more stable configuration as they are now. Migration in the Nice model involves a limited outward migration of Saturn and outward migration of Uranus and Neptune. The migration is associated with changes in the orbital eccentricities of Saturn, Neptune, and Uranus as well. Though today Saturn's orbital eccentricity is 0.052, the Nice model suggests it reached a maximum of 0.12. Though Neptune today has an orbital eccentricity of 0.004, the Nice model suggests it reached 0.04. These changes in eccentricity may not seem very significant but they are enough to have significant effects due to orbit resonances between the four outer planets. The higher eccentricities are believed to have eventually been reduced to the present values due to dynamical friction, as planetesimals are scattered by the planets. Though the Grand Tack scenario encompasses a period of approximately 600,000 years, the Nice scenario covers a period of approximately 100 million to 700 million years.

Before the application of planet migration models, the formation of the four outer planets tended to have difficulty with the protosolar disk dissipating before the planets could reach their full present size (Spencer 1994, p. 517). Taylor (1992) summarizes the state of the research in 1992 as follows. "Other estimates for the times taken to form a 10-Earth-mass core are 700,000 years for Jupiter, 3.8 m.y. for Saturn, 8.4 m.y. for Uranus, and 23 m.y. for Neptune" (p. 16-17). Note that this is not the time for the planet to reach its full size and mass, but the time for a 10-Earth-mass core to form. If gas dissipated in the outer region of the disk in less than 8 million years, then Uranus and Neptune would not be likely to reach their present size. The disk has always been modeled as thicker and denser near the Sun and thinning with increasing distance. Thus models prior to orbit migration had the most difficulty reproducing the present masses of Uranus and Neptune. A more recent study estimated Jupiter could reach its full mass in a time from 1 to 5 million years (Hubickyj, Bodenheimer, and Lissauer 2005). In the Nice model the protoplanetary disk, consisting of planetesimals, is assumed to be more dense and more massive than in older models. Also, the four outer planets start forming nearer to the Sun and nearer to each other, which puts them in regions more dense than in older solar system models. Note that the initial orbital positions of the four outer planets are usually free parameters chosen at the start of the simulations, and various orbital starting positions have been modelled.

Another issue addressed by the Nice model is the origin of the Trojan asteroids of Jupiter. A large number of asteroids exist near the L4 and L5 Lagrange Points of the Jupiter orbit. The L4 position is a 60° angle ahead of Jupiter along Jupiter's orbit. The L5 position lies at 60° behind Jupiter along the orbit. The Jupiter Trojans (also sometimes called coorbitals) orbit near these two positions, generally oscillating around them. Any planet can have small bodies in or near the L4 and L5 positions. In recent years Trojan asteroids have been found sharing the orbits of Venus (de la Fuente Marcos and de la Fuente Marcos 2014), Earth (Connors, et. al. 2011), Mars (Connors, et. al. 2005), Uranus (Alexandersen, et. al. 2013), and Neptune (Guan, Zhou, and Li 2012). The total number of Jupiter Trojans has been estimated as on the order of 600,000, however this is an estimate, not actual known objects. Jupiter Trojans that have actually been observed are listed on the IAU Minor Planet Center website, with 6,521 objects as of 9/24/2017. The other planets in our solar system only have small numbers of known Trojan companions to date.

The Trojan asteroids of Jupiter (and of Uranus and Neptune) are taken to be evidence in support of the Nice model. The Nice model presumes that when Jupiter formed in the protosolar disc, many small bodies formed in its vicinity and some small percentage of these objects were captured into the L4 and L5 regions. Various studies considered the effect of orbit migration of the outer planets on Trojan asteroids. Simulations show that some Trojan asteroids can survive the migration of their planet. This is especially true for Jupiter and Neptune. However, simulations starting Saturn with Trojan asteroids almost always lead to the loss of the Saturn Trojans. After the outward migration of Jupiter and Saturn in the Grand Tack, a new population of Trojan asteroids would be captured by Jupiter (Morbidelli, et. al. 2005).

In the Nice model, most of Jupiter's early collection of Trojan asteroids would have been lost during Jupiter's migration. But because Saturn, Uranus, and Neptune are being caused to migrate by a large population of planetesimals scattering off them, it would be expected that temporary Trojan asteroids could exist. The Nice model assumes that there was a very massive belt of large planetesimals in the outer solar system. This region, sometimes now referred to as the transneptunian region, today has objects totaling only approximately one tenth of an Earth mass (Gladman, et. al. 2001). But in the Nice model this region is assumed to include a large population of objects totaling approximately 35 Earth masses (Gomes, et. al. 2005). As Saturn migrates outward in the Nice model, it eventually reaches a more stable orbit as it gets farther from the 2:1 resonance with Jupiter. Uranus and Neptune also get farther apart and the planetesimals eventually become depleted in the transneptunian region. Thus, the Trojans of Jupiter would have represented a changing population of temporary Trojans, until outer planet migration stopped. Then the Trojans left at the end of the migrations of Saturn, Uranus, and Neptune are the objects observed today.

The Nice model also argues that the Late Heavy Bombardment (LHB) of impacts in the inner solar system could have been caused by the instability among planetesimals that was due to outer planet migration. This aspect of the Nice model is still being debated today. To connect outer planet migration to the LHB, it is argued that the time of when Saturn crossed the 2:1 resonance could have

been delayed by several hundred million years by the migration being initially very slow. Simulations of the Nice migration show that Saturn, Uranus, and Neptune can migrate very slowly for some period of time, then as Neptune begins to penetrate into the outer disk of planetesimals the migration of Uranus and Neptune accelerates. In the Nice model as first proposed, the position of the inner and outer edges of this disk of solid objects affects the timing of when Saturn crosses the 2:1 resonance with Jupiter. So, if the inner edge of the planetesimal disk is farther from the Sun, the Saturn crossing of the 2:1 resonance would happen later (Gomes, et. al. 2005, p. 467). Once Saturn passes the 2:1 resonance, other resonances between Saturn and Uranus and Saturn and Neptune occur that alters their orbits and accelerate the outward migration. The resonances under migration cause an increase in the eccentricity of Saturn, Uranus, and Neptune. The effect is to make resonances move across the outer solar system, causing the orbits of many planetesimals to destabilize and scatter in various directions. Computer simulations have been done that demonstrate these processes. These scattered planetesimals would cause many impacts in the outer solar system and some in the inner solar system. The planetesimals from the outer region could interact with objects in what is now the asteroid belt, so that asteroids interior to Jupiter's orbit could also cause impacts.

3. **Recent Extensions of the Models**

A number of variations on the Nice model have been attempted since it was originally published. The rate and timing of the outer planet migration has been the focus of much study. A number of possible initial conditions for the outer planets at the start of the Nice model have been examined in simulations. A consensus seems to be emerging that Jupiter, Saturn, Uranus, and Neptune were all in some combination of a chain of resonances at the time of the dissipation of the gas in the solar disk (Batygin and Brown 2010 p. 1331). Each of the outer planets would have resonances with their nearest neighbors. This multi-resonant migration has been referred to as the Nice II model (Levison, et. al. 2011 p. 153). The outer planet resonances and the initial outer planet positions have a significant effect on the timing of their migration. Some researchers have expressed doubts about the planetesimal scattering of the Nice model causing the Late Heavy Bombardment. The doubts have been raised because the migration of the outer planets could have ended before the time of the LHB. It has also been discovered that the resonances between the outer planets can have an effect of increasing the eccentricities of the inner planets and the asteroids.

Another variation on the Nice model by some researchers is to include more than four outer planets, some of which were lost. The most common scenario examined has been to consider there being one additional outer planet similar to Uranus or Neptune in size that existed beyond Saturn. This "fifth" gas giant (similar to Uranus or Neptune) would interact with Saturn and then Jupiter so that Jupiter eventually ejects it out of the solar system (Nesvorny, 2011). The fifth gas giant would then become a rogue planet. The advantage of this additional outer planet is to cause Jupiter and Saturn to separate in a short time. This has been called the "Jumping Jupiter" scenario. Because the orbit changes undergone by this fifth planet would take it inside the orbit of Jupiter it could affect the inner solar system and interact chaotically with Jupiter and Saturn.

The Grand Tack and Nice models are considered to be very successful in explaining a number of important aspects of our solar system. The incorporation of planet orbit migration has revolutionized theories on the origin of our solar system. Though variations on these two models are still being explored, there is wide agreement among planetary scientists that these models are successful in their main aspects. Following are some of the characteristics of our solar system that are understood as successfully explained in these new models.

- Orbital distances to the four outer planets as well as their masses
- The low mass of Mars
- The origin of the Trojan asteroids of Jupiter (and the other planets)
- The composition distribution of the main asteroid belt
- The cause of the Late Heavy Bombardment
- The distribution of objects in the trans-Neptunian region
- The current low total mass of the asteroid belt and the trans-Neptune belt
- Orbits of the moons of Saturn
- The resonance relationship of Pluto with Neptune

DISCUSSION

1. Biblical Considerations

The new Grand Tack and Nice models for the origin of our solar system are clearly in conflict with Scripture. First, the possibility of our solar system being intelligently designed is not considered. The goal seems to be to treat the origin of our solar system in the same manner as the origin of extrasolar planetary systems. But Isaiah 45:18 is clear that God created the Earth with the expressed purpose that it be inhabited. Isaiah 45:18 (NIV) states, "For this is what the LORD says— he who created the heavens, he is God; he who fashioned and made the earth, he founded it; he did not create it to be empty, but formed it to be inhabited . . . ." Secondly, both the Genesis creation account and Exodus 20:11 place the formation of all things within the six days of God's creative activity. Both the Old and New Testaments reinforce the historicity of Genesis and rule out Earth being millions or billions of years old. The author would take the age of the Earth as in the range of 6,000 to 8,000 years. In this framework, there would not be time for the Grand Tack model or the Nice model to take place, even assuming the validity of it as a physical process. In addition, the Genesis creation account ends with the statement, "Thus the heavens and the earth were completed in all their vast array (Genesis 2:1, NIV)." These passages seem to argue against there being a long period in which the Earth was uninhabitable. The creation account only has Earth uninhabited by humans for five days as the environment is being prepared by God. Then Genesis 2:1 indicates that not only was the Earth completed by the end of the creation week, but all of the physical creation was completed. Biblically, Earth was formed and prepared for habitation by supernatural processes in the creation week. The Bible does not describe the formation of solar system objects other than the Sun and Moon. However, it is reasonable to assume that they would have been formed on the fourth day of the creation week as was the Moon (Spencer 2014a). Therefore, we can say the Bible implies the formation of our solar system was extremely rapid and unlike all naturalistic theories, Earth formed

first according to Genesis, followed by other objects. This is a counter-intuitive process in Genesis that makes mankind the focus of God's creative activity.

2. Limitations of the Computer Models

The Grand Tack and Nice models are based entirely on computer simulations that are constructed to attempt to show how a planetary system like our own could arise by natural physical processes. These models are built on a number of assumptions that determine a specific sequence of processes. Though real physics is put into the computer programs used, these models have been arrived at through much trial and error, varying the initial conditions and parameters input into the simulations. Many observations about our own solar system as well as extrasolar planetary systems have been in view in the development of these new migration theories. The Grand Tack and Nice models therefore do not predict characteristics of our solar system, rather they attempt to adapt to the observed characteristics of the solar system. These models assume a specific history of our solar system. This history cannot be verified by observations. But scientists who are advocating these new theories would say that this new paradigm incorporating planet migration is more successful than other approaches used in the past.

Computer simulations of planet formation itself begin assuming that planetesimals and planetary embryos already exist. Yet the formation of these solid objects has not been explained. The planetesimals are often assumed to be 1 km in diameter and sometimes are assumed to be as large as 10 km diameter at the start of the simulation. Planet embryos are assumed to be of a variety of sizes, generally ranging from approximately the mass of our Moon to the mass of Mars. It is usually assumed that there are many more planetesimals than embryos. Fragmentation of solid objects in collisions is usually ignored in the simulations. All collisions with a planetary embryo (both planetesimal to embryo and embryo to embryo) are assumed to result in a merging of the two objects onto the embryo. This is thought to be a valid approximation considering that the mass of the embryos is much greater than the mass of the planetesimals. The author would question this assumption. It is interesting to note that the proposed origin of our Moon by an impact involves a case where a planetary embryo collides with Earth and does not completely merge with the Earth. Then the ejecta reforms into our Moon. This type of impact scenario is not considered as a general case across the solar system in the Grand Tack or Nice simulations, though this theory for the formation of our Moon is widely accepted.

The computer simulations make many simplifying assumptions regarding what happens in a disk which consists of a mixture of gas, dust, and larger solid objects. When simulations examine the migration of planets in a gaseous disk, accretion of gas onto the planet at the same time is usually neglected. Accretion of the planet during this process could change what happens in the migration. Raymond and Morbidelli (2014) mentioned this limitation, "Hydrodynamical simulations of planet migration do not have the requisite resolution to realistically include gas accretion, yet these two are intimately coupled in the Grand Tack model. This is a key uncertainty for the Grand Tack; it is unclear whether long-term outward migration of Jupiter and Saturn is possible given the stringent mass ratio requirement"(p.197). The mass ratio requirement here refers to the ratio of the mass of Jupiter to the mass of Saturn. Simulations consistently show that this mass ratio has a major effect on the migration of Jupiter and Saturn. This suggests many outcomes would be possible, if the masses of Jupiter and Saturn had been sufficiently different.

Several aspects of the Grand Tack and Nice models seem to require special timing in order for the desired result to be obtained in the end of the simulations. One ongoing question regarding timing is around the question of when did Jupiter form in the protoplanetary disk? Jupiter must reach nearly it's full mass before the inward migration of Jupiter begins in the Grand Tack. This becomes important because the gas in the disk is required to remain available until Jupiter and Saturn have completed their outward migration in the Grand Tack. Thus, the gas in the disk must last long enough for Jupiter and Saturn to migrate through it twice. This tends to necessitate Jupiter's formation being rather rapid. If the gas in the disk dissipated too quickly, Jupiter and Saturn might not migrate outward far enough. Not only would this lead to different orbits for the outer planets, it could affect the orbits of Earth and Mars due to their proximity to Jupiter and it could prevent the Nice scenario from occurring.

Other issues of timing could affect the Nice model. The resonance between Jupiter and Saturn during their outward migration in the Grand Tack is assumed to be a 2:3 resonance. But the start of the Nice model is usually implemented with Jupiter and Saturn crossing their 1:2 resonance. It is not clear how the transition between these two resonances would take place. In the Grand Tack, Jupiter and Saturn clear objects out of the asteroid belt as they migrate inward. Then as they migrate back out again, they scatter planetesimals outward. The outward migration in the Nice model depends on the availability of planetesimals in the outer disk. The outer part of the disk is assumed to start with a large mass of planetesimals, on the order of 20 to 35 Earth masses in planetesimals. In the Nice model, resonances between Saturn, Uranus, and Neptune can lead to many outcomes for the final state of the planets. Simulations have shown that if the initial positions of the outer planets are closer together this tends to make their influence on each other via resonance greater and migration is more rapid. But if they are farther apart at the start then they migrate less because they reach stability sooner. Multiple resonances such as this are imposed on the simulations as starting conditions or by varying the disk properties. In a forming planetary system these resonances may or may not occur. Furthermore, the simulations presuppose resonances that do not actually exist among the real planets in our solar system.

Another question of timing regarding the Nice model is a point of ongoing debate, the cause of the Late Heavy Bombardment of impacts in the inner solar system. One of the extensions to the Nice model is to modify the parameters of the simulation to delay when Saturn crosses the 1:2 resonance with Jupiter. This makes Neptune reach the inner edge of the outer planetesimal belt at a later time so as to be able to cause the Late Heavy Bombardment (LHB) impacts. In the original Nice model Neptune would reach the inner edge of the planetesimal disk at approximately 100 MY after the start of the Nice migration. Later modifications to the model push this time to approximately 700 MY after the start of

the Nice migration. This change was made by modifying input parameters such as the eccentricities of the planetesimal orbits, starting Saturn, Uranus, and Neptune slightly closer together, and slightly adding to the mass of the planetesimal disk (Gomes, 2005, p. 467).

However, a more recent paper raises questions as to whether the Nice model can explain the Late Heavy Bombardment. Kaib and Chambers (2016) model both the inner planets and the outer planets in the same extended Nice model simulations. Most prior studies examine only the outer planets in the Nice model simulations. With the terrestrial planets included it was found that the orbits of Jupiter and Saturn become more eccentric due to the global instability which scatters planetesimals in the outer solar system. The outer planets affect each other's orbits in this scenario because of the mutual resonances between them. The instability in the outer solar system causes the precession rate to change in Jupiter's orbit and this makes Jupiter pass through resonances with the terrestrial planets. The effect of this is to make the inner planet orbits more eccentric than the actual orbits today, especially Mercury and Venus. Thus, changes in the orbits of the outer planets in the Nice model could conceivably affect Earth. Thus, the authors of this study argue that the planetesimal instability of the Nice model does not explain the Late Heavy Bombardment and that the instability must have occurred earlier before the terrestrial planets had completed their formation.

3. The Protoplanetary Disk

The Grand Tack and Nice models depend critically on the protoplanetary disk of gas and dust that the planets form from. The so-called Minimum Mass Solar Nebula (MMSN) used for the past 30 years assumes the outer planets formed at their current locations. Thus, scientists are aware of the need to modify the MMSN model to be appropriate for the new planet migration models. An attempt to do this was made by Desch, (2007). The planets were assumed to start in orbital positions as in the Nice model, then the necessary mass surface density profile for the disk was estimated as a function of distance. The resulting power law derived by Desch has a surface density nearly 10 times that of the original MMSN at 5.45 A.U. (Jupiter) and nearly 4 times that of the original MMSN at 22 A.U. (the vicinity of Neptune late in the Nice migration). This denser disk seems to work well in Desch's approach for the accretion of the outer planets, because it is a long-lived disk. However, it leads to a serious problem. In the Desch disk, the density is so great that Jupiter migrates inward rapidly by the Type III mechanism and spirals into the Sun in only a few hundred years! The other outer planets also all spiral into the Sun in less than 20,000 years (Crida, 2009). Crida (2010) makes the statement that "I would claim that a new Solar Nebula consistent with the Nice model is still to be built" (p. 222). Thus, unresolved questions remain regarding how the disk can provide enough material for the gas giants to form and also support orbit migration in the right manner to lead to the planets as we find them today.

CONCLUSION

The Grand Tack and Nice models are considered to be very successful in explaining a number of major characteristics of our solar system. However, these models require many special conditions that are chosen by the investigator. They involve a prescribed sequence of events that includes four different mechanisms of planet orbit migration, Type I, Type II, planetesimal scattering, and planet-planet resonances. Though the Grand Tack and Nice models employ methods that have been applied in extrasolar planet research, no extrasolar planetary system has been proposed to involve all four of these migration mechanisms. Many special conditions are input into the simulations by the investigator to make the scenario succeed. In many ways the end result is in mind as the conditions of the simulation are started. This could be considered inappropriate investigator interference since in the real primordial solar system, there would be no agent to set up the proper conditions. For example, the extremely compact extent of the protoplanetary disk, compared to real observed disks, is unrealistic. The protoplanetary disk assumed in the Grand Tack and Nice models is only approximately 30 to 40 A.U. in radius. But observed debris disks around other stars are commonly much larger. Though the physics of planet migration may be valid, there is reason to doubt whether the conditions necessary for orbit migration can plausibly exist in real disks. For our solar system the entire process seems implausibly fortuitous. The author does not accept that orbit migration of planets occurred in our solar system. Instead supernatural creation seems necessary. It could be argued that even if our solar system did form from such a complex planet migration process it would be evidence of intelligent design. The migration simulations, rather than giving evidence of the means of formation of our solar system, should be viewed as giving information about cause and effect relationships in the solar system. Jupiter, with its large mass and strategic placement just past 5 A.U. has a stabilizing effect on both the inner and outer planets. The planets as we find them today are in orbits that are quite stable and orbit resonance relationships are not significant. The Grand Tack and Nice models also deal with broad patterns in the solar system such as the distribution of the various types of asteroids in the asteroid belt and the trans-Neptunian belt. But there are unique qualities of various bodies in the solar system that are not explained by these new models because planet migration is not relevant to those features. Examples of this would be the peculiar spin axes of Venus and Uranus. Also, the rings of the outer planets would have to be viewed as having formed after most of the migration was completed in the Nice model. There has been some research on forming the so-called "irregular" moons of the outer planets under the Nice scenario (Nesvorny, Vokrouhlicky, and Morbidelli 2007). However, many moons in the solar system have very "regular" circular orbits, they are not significantly eccentric or inclined, compared to their planet. Some moons could form early prior to migration and survive the migration of the planet, but it seems doubtful to the author that their final orbits would be nearly circular and coplanar.

It is also worth noting that in running the same simulations over and over the same result is not obtained on each run. In some runs of the Grand Tack model one of the four inner planets can be ejected from the system (most frequently Mercury). Indeed, in the Grand Tack some planet embryos or small planets could have fallen into the Sun. Another issue is the final eccentricities and inclinations of the planets. During migration, the migrating planets have higher eccentricities than the actual planets today. It is assumed that these somewhat more eccentric orbits would be

rounded by the scattering of planetesimals. But this depends on how dense the planetesimal disk is and how long it endures. After the global instability of the Nice model the planetesimals would be dramatically less dense in the disk because many of them would be scattered out of the solar system completely. Thus, planetesimals may not effectively round off the orbits.

Young age creationists can view our solar system under a much simpler paradigm than in the Grand Tack and Nice models. Genesis implies God's supernatural creative activity was complete at the end of the creation week. Our solar system is intelligently designed to be a remarkably safe and stable system. The migration simulations show that any change in Jupiter's orbit has a significant effect on all the other planets. Thus, Jupiter seems to act as a kind of dynamic anchor to the other planets. The various planets and moons in our solar system give us glimpses of the variety God created and show how unique our own planet is. On the other hand, there are possibilities that could be explored regarding changes in the orbits of small bodies after creation. For example, if asteroids were started at creation in various distributions, how long would be required for approximately 6,500 Trojans to collect at the L4 and L5 Lagrange points of Jupiter? More insights could be gained from creationists reproducing some of the planet migration scenarios. However, the author believes that migrating planets are not necessary for explaining our solar system.

REFERENCES

Alexandersen, M., B. Gladman, S. Greenstreet, J.J. Kavelaars, J.M. Petit, and S. Gwyn. 2013. A Uranian Trojan and the frequency of temporary giant-planet co-orbitals. *Science* 341, no. 6149: 994-997.

Batygin, K., and M.E. Brown. 2010. Early dynamical evolution of the solar system: Pinning down the initial conditions of the Nice Model. *The Astrophysical Journal* 716, no. 2: 1323-1333.

Blum, J., R. Schrapler, B.J.R. Davidsson and J.M. Trigo-Rodriguez. 2006. The physics of protoplanetesimal dust agglomerates I. Mechanical properties and relations to primative bodies in the solar system. *The Astrophysical Journal* 652:1768-1781.

Clanton, C., and B.S. Gaudi. 2017. Constraining the frequency of free-floating planets from a synthesis of microlensing, radial velocity, and direct imaging survey results. *The Astrophysical Journal* 834:46, no. 1:-13.

Connors, M., G. Stacey, R. Brasser, and P. Wiegert. 2005. A survey of orbits of co-orbitals of Mars. *Planetary and Space Science* 53, no. 6: 617-624.

Connors, M., P. Wiegert, and C. Veillet. 2011. Earth's Trojan asteroid. *Nature* 475:481-483.

Crida, A. 2009. Minimum mass solar nebulae and planetary migration. *The Astrophysical Journal* 698:606-614.

Crida, A. 2010. Solar system formation. In *Reviews in Modern Astronomy: Formation and Evolution of Cosmic Structures* [vol. 21], ed. S. Roser, pp. 215-227. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA.

de la Fuente Marcos, C., and R. de la Fuente Marcos. 2014. Asteroid 2013 ND15: Trojan companion to Venus, PHA to the Earth. *Monthly Notices of the Royal Astronomical Society* 439, no. 3:2970-2977.

Desch, S.J. 2007. Mass distribution and planet formation in the solar nebula. *The Astrophysical Journal* 671:878-893.

Faulkner, D.R. 2014. Interpreting craters in terms of the Day Four cratering hypothesis. *Answers Research Journal* 7:11-25.

Fog, M.J., and R.P. Nelson. 2007. The effect of type I migration on the formation of terrestrial planets in hot-Jupiter systems. *Astronomy and Astrophysics* 472:1003–1015.

Gladman, B., J.J. Kavelaars, J.M. Petit, A. Morbidelli, M.J. Holman, and T. Loredo. 2001. The structure of the Kuiper Belt: Size distribution and radial extent. *The Astronomical Journal* 122, no. 2:1051-1066.

Goldreich, P., and S. Tremain. 1980. Disk-satellite interactions, part I. *The Astrophysical Journal* 241:425-441.

Gomes, R., H.F. Levison, K. Tsiganis, and A. Morbidelli. 2005. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* 435:466-469.

Guan, P., L.Y. Zhou, and J. Li. 2012. Trailing (L5) Neptune Trojans: 2004 KV18 and 2008 LC18. *Research in Astronomy and Astrophysics* 12, no. 11: 1549-1562.

Hasegawa, Y., and S. Ida. 2013. Do giant planets survive Type II migration? *The Astrophysical Journal* 774:146-155.

Hayashi, C. 1981. Formation of the planets in fundamental problems in the theory of stellar evolution. *Proceedings of IAU Symposium No. 93* [Kyoto, Japan July 22-25, 1980], pp. 113-128. Dordrecht:D. Reidel.

Hubickyj, O., P. Bodenheimer, and J.J. Lissauer. 2005. Accretion of the gaseous envelope of Jupiter around a 5–10 Earth-mass core. *Icarus* 179, no. 2:415-431.

Izidoro, A., S.N. Raymond, A. Morbidelli, and O.C. Winter. 2015. Terrestrial planet formation constrained by Mars and the structure of the asteroid belt. *Monthly Notices of the Royal Astronomical Society*, 453: 3619–3634.

Jacobson, S.A, and A. Morbidelli. 2014. Lunar and terrestrial planet formation in the Grand Tack scenario. *Philosophical Transactions of the Royal Society A*, 372, no. 2024, rsta.2013.0174.

Kaib, N.A., and J.E. Chambers. 2016. The fragility of the terrestrial planets during a giant-planet instability. *Monthly Notices of the Royal Astronomical Society* 455:3561-3569.

Levison, H.F., A. Morbidelli, R. Gomes, and D. Backman. 2007. Planet migration in planetesimal disks. In *Protostars and Planets V,* eds. B. Reipurth, D. Jewitt, and K. Keil, pp. 669-684. Tucson: University of Arizona Press.

Levison, H.F., A. Morbidelli, C. Van Laerhoven, R. Gomes, and K. Tsiganis. 2008. Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune. *Icarus* 196, no. 1:258-273.

Levison, H.F., A. Morbidelli, K. Tsiganis, D. Nesvorny, and R. Gomes. 2011. Late orbital instabilities in the Outer Planets induced by interaction with a self-gravitating planetesimal disk. *The Astronomical Journal* 142:152-163.

Lewis, J.S. 2004. *Physics and Chemistry of the Solar System,* 2nd ed. London: Elsevier Academic Press.

Liu, M.C., E.A. Magnier, N.R. Deacon, K.N. Allers, T.J. Dupuy, M.C. Kotson, K.M. Aller, W.S. Burgett, K.C. Chambers, P.W. Draper, K.W. Hodapp, R. Jedicke, N. Kaiser, R.P. Kudritzki, N. Metcalfe, J.S. Morgan, P.A. Price, J.L. Tonry, and R.J. Wainscoat. 2013. The extremely red, young L dwarf PSO J318-22: A free-floating planetary-mass analog to directly imaged young gas-giant planets. *The Astrophysical Journal Letters* 777, no. 2:L20.

Matsuo, T., H. Shibai, T. Ootsubo, and M. Tamura. 2007. Planetary formation scenarios revisited: Core-accretion versus disk instability.

The Astrophysical Journal 662:1282-1292.

Minor Planet Center. Trojan minor planets, Retrieved September 24, 2017 from http://www.minorplanetcenter.org/iau/lists/Trojans.html.

Morbidelli, A., H.F. Levison, K. Tsiganis, and R. Gomes. 2005. Chaotic capture of Jupiter's Trojan asteroids in the early Solar System. *Nature* 435 (May 26):462-465.

Morbidelli, A., K. Tsiganis, A. Crida, H.F. Levison, and R. Gomes. 2007. Dynamics of the giant planets of the solar system in the gaseous protoplanetary disk and their relationship to the current orbital architecture. *The Astronomical Journal* 134:1790-1798.

Nesvorny, D., D. Vokrouhlicky, and A. Morbidelli. 2007. Capture of irregular satellites during planetary encounters. *The Astronomical Journal* 133:1962-1976.

Nesvorny, D. 2011. Young solar system's fifth giant planet? *The Astrophysical Journal Letters* 742:L22-L28.

Papaloizou, J.C.B., R.P. Nelson, W. Kley, F.S. Masset, and P. Artymowicz. 2007. Disk-planet interactions during planet formation. In *Protostars and Planets V,* eds. B. Reipurth, D. Jewitt, and K. Keil Tucson, pp. 655-668. Tucson: University of Arizona Press.

Poppe, T., J. Blum, and T. Henning. 2000. Analogous experiments on the stickiness of micron-sized preplanetary dust. *The Astrophysical Journal* 533:454-471.

Raymond, S.N., and A. Morbidelli. 2014. The Grand Tack model: A critical review. *Proceedings of the International Astronomical Union* 9, no. S310:194-203.

Spencer, W.R. 1994. The origin and history of the solar system. *Proceedings of the Third International Conference on Creationism*, ed. R.E. Walsh, pp. 513-523. Pittsburgh, Pennsylvania: Creation Science Fellowship.

Spencer, W.R. 2001. The existence and origin of extrasolar planets. *Journal of Creation* 15, no. 1:17–25.

Spencer, W.R. 2007. Migrating planets and migrating theories. *Journal of Creation* 21, no. 3:12-14.

Spencer, W.R. 2008. Our solar system balancing biblical and scientific considerations. *Proceedings of the Sixth International Conference on Creationism*, ed. A.A. Snelling, pp. 293-306. Pittsburgh, Pennsylvania: Creation Science Fellowship.

Spencer, W.R. 2010. The search for earth-like planets. *Journal of Creation* 24, no. 1:72-76.

Spencer, W.R. 2011. Retrograde exoplanets challenge theories. *Answers in Depth* [February 23, 2011], https://answersingenesis.org/astronomy/extrasolar-planets/retrograde-exoplanets-challenge-theories/.

Spencer, W.R. 2014a. Evaluating the Day Four cratering hypothesis. *Answers Research Journal*, 7:323-329.

Spencer, W.R. 2014b. Critique of modern Oort comet theory. *Creation Research Society Quarterly* 50, no. 3:146–153.

Spencer, W.R. 2017. The Challenges of extrasolar planets. *Creation Research Society Quarterly* 53, no. 4:272-285.

Taylor, S.R. 1992. *Solar system evolution: A new perspective*. Cambridge University Press.

Tsiganis, K., R. Gomes, A. Morbidelli, and H.F. Levison. 2005. Origin of the orbital architecture of the giant planets of the solar system. *Nature* 435:459-461.

Walsh, K.J., A. Morbidelli, S.N. Raymond, D.P. O'Brien, and A.V. Mandell. 2011. A low mass for Mars from Jupiter's early gas-driven migration. *Nature* 475:204-209.

Walsh, K.J., A. Morbidelli, S.N. Raymond, D.P. O'Brien, and A.V. Mandell. 2012. Populating the asteroid belt from two parent source regions due to the migration of giant planets – "The Grand Tack." *Meteoritics & Planetary Science*, 47, no. 12:1941–1947.

Walsh, K.J., A. Morbidelli, S.N. Raymond, D.P. O'Brien, and A.V. Mandell. 2012. Populating the asteroid belt from two parent source regions due to the migration of giant planets – "The Grand Tack." *Meteoritics & Planetary Science*, 47, no. 12:1943–1944.

Weidenschilling, S.J. 1977. The distribution of mass in the planetary system and solar nebula. *Astrophysics and Space Science* 51 no. 1:153-158.

Zahnle, K., N. Arndt, C. Cockell, A. Halliday, E. Nisbet, F. Selsis, and N.H. Sleep. 2007. Emergence of a habitable planet. *Space Science Reviews* 129:35-78.

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