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MIGRATING PLANETS

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1. NEBULAR HYPOTHESIS AND PROTOPLANETARY DISKS

Among the pioneers of the idea of swirling vortices of gas being responsible for the formation of the solar system was Descartes (1644). In his treatise, he speculated that God sent clouds adrift which changed into comets and planets. Although lacking scientific detail, parallels can be observed with nebular hypotheses proposed almost a century later by Swedenborg (1734) and, later, Kant (1755) using Newtonian principles. The first to develop a model of the rotating gaseous nebula collapsing and evolving into a planetary system was, however, Laplace (1796) who did it in a rigorous mathematical way. Although recent history of cosmological theories includes many contrasting alternatives (Buffon 1745; Chamberlin 1901; Jeans 1928; Jeffreys 1929; Whipple 1948), scientific consensus appears to be emerging on how the solar system evolved into its current state.

The nebular hypothesis remains the most widely accepted framework explaining the formation of the solar system (Bodenheimer 2006). Within it, many of the basic features of the solar system can be explained naturally: planets revolving and rotating mostly in the same direction, all having the same orbital plane. It is widely accepted that new stars form through the gravitational collapse of a dense molecular cloud core. Because of the core having certain angular momentum, most of the matter will not fall onto the protostar but will form a circumstellar disk, also known as the proplyd (Dullemond et al. 2007). Observations of proplyds (see figure 1) provide evidence of the nebular hypothesis in action and imply the solar system must have also been formed in a similar way. Recent studies revealed that the fraction of stars of 0.1–3 $M_\odot$ masses and ages of < 1 Myr surrounded by circumstellar disks approaches 100% (Strom 1995). At the current moment 170 disks have been resolved and confirmed with direct observations (Stapelfeldt 2013).

2. PLANET FORMATION

Traditionally, our understanding of the process of planet formation is divided into four stages that may occur simultaneously at different radii across the proplyd: (i) dust sedimentation and growth, (ii) planetesimal growth, (iii) planetary embryo growth, and (iv) planet growth (Jacobson & Walsh 2015). The standard scenario for solar system formation established between the 1960s and the 1980s is based on a) the planetesimal hypothesis with terrestrial planets forming from planetesimals, and b) the core accretion model—gas components of gas giants were added after rocky or icy cores accrete from planetesimals (Pollack et al. 1996; Kokubo & Ida 2012). The process begins with dust, ice and gas from sedimenting in the vertical mid-plane of the proplyd

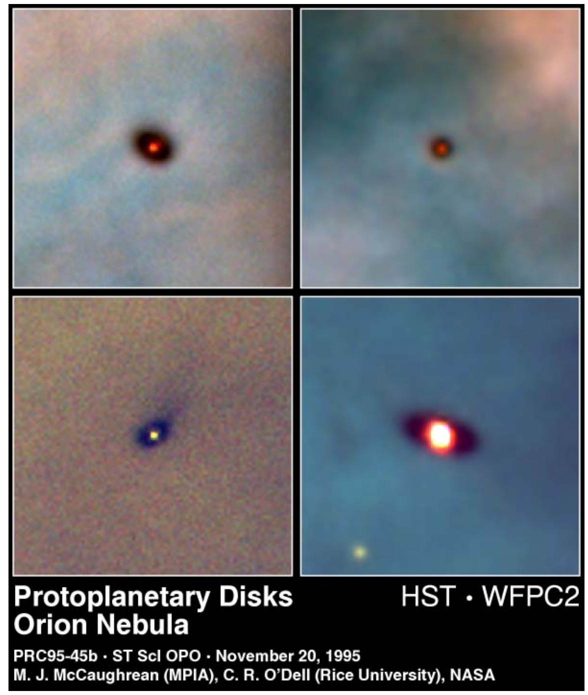

Figure 1. Narrowband images of proplyds around young stars in the Orion nebula from *HST* (McCaughrean & O'Dell 1996).

(Weidenschilling 1980). The dust and ice grains grow by colliding and "sticking" with each other, resulting in a population of boulders and pebbles. They experience headwind from the gas orbiting at slower sub-Keplerian velocities, loose energy and spiral inwards (drift radially) into the host star. At a certain distance—contingent to the stellar mass and subject compound—a "snow line" is formed whereby water and other volatiles are boiled off (Kennedy & Kenyon 2008). The line separates the inner region of terrestrial planet formation from the outer region of gas giants and icy planets. An important feature of the snow line is that material tends to condense there (Cuzzi & Zahnle 2004), so it is a favorable place for planet formation.

It is believed that out of the boulders and pebbles of sizes ranging from centimeters to meters, ∼100–1000 km planetesimals were formed – bodies that are held together by self-gravity rather than material strength (Morbidelli et al. 2009). It has proven difficult to develop realistic model of their formation and growth primarily due to two problems: fragmentation and bounce, and rapid inward migration. When objects increase in size, aerodynamical drag decreases, impact velocities increase and boulders bounce or fragment when they collide instead of coagulating together. This is often referred to as the "bouncing barrier", restricting growth to a maxi-

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mum of ∼0.1–1 m. Due to radial drift, larger objects will migrate and spiral inward into the star faster – during a few hundred orbits only. Various models are proposed to address this. In a model proposed by Wurm et al. (2005), a collision between small projectile and large target will still result in fragmentation, however some mass of the projectile will stick to the target, enabling net growth of planetesimals. Wada et al. (2008) proposed a model based on dust having high degree of coupling with the rotating gas disk and slower collisions of fluffy particles. For a more detailed overview of planetesimal growth, I recommend works by Johansen et al. (2014); Windmark et al. (2012).

Planetesimals collide and coagulate (or fragment), and some of them grow to Moon-to-Earth sized planetary embryos. Core accretion model implies that embryos start with a burst of rapid runaway growth—largest bodies grow faster—after which follows a transient stage, and then settle on a slower asymptotic growth regime as they start to divert planetesimals in their vicinity away from their path (Rafikov 2003). This results in an oligarchic population of embryos of comparable sizes, competing for the remaining planetesimals. As planetesimal population has been depleted—either through accretion or scattering—embryos begin to perturb each other onto crossing orbits, resulting in scattering or giant impact (GI) events, consistent with, for example the GI hypothesis of the Moon formation (Bottke et al. 2014).

Formation of the first gas giants has a profound impact on the shape of the rest of the planetary system. In the core accretion model, gas giants are formed from embryos (cores) when they grow massive enough to capture nebular gas gravitationally (Alibert et al. 2005). Jupiter has accumulated $\approx 300 M_{\oplus}$ until Sun has had enough time to blow away all the gas from its proplyd. As core grows orbiting inside the gaseous environment, it creates density waves that make it loose energy and spiral inwards into the star in what is called type I migration. The growth of a giant stabilizes when the planet becomes massive enough to open up a gap in the nebular disk. The gas would still "ooze" into the gap and cause the planet to loose energy and continue to spiral inwards – the much slower migrational process referred to as type II. The initial gas giant helps other giants to emerge in the system: by opening the gap at the end of type I migration, the pressure at the outer edge of the gap is increased and material accumulates there. It also swings planetesimals to outer orbits, feeding second generation giants.

3. SOLAR SYSTEM: THE GRAND TACK AND NICE SOLUTION

While nebular and planetesimal hypotheses and the core accretion model provide us with a solid foundation to understand the formation of planetary systems in general, certain peculiarities of our own called for further analysis. A longstanding mystery, for example, was the reason why, due to the type II migration, Jupiter, Saturn, Uranus and Nepute have not spiraled all the way into the Sun. In general, how do we explain bulk orbital properties of the planets and also the Late Heavy Bombardment (LHB)? In the trilogy of papers the Nice model addresses these questions via compact configuration of giants orbiting in mean motion resonance (MMR). This was based on the earlier discovery that type II migration can actually be reversed if giants orbit in certain MMR configurations in a common gap (Masset & Snellgrove 2001). In the model, after the gas has been dissipated from the proplyd, giants are found on quasi-circular orbits with Neptune well inside 20 AU, closer to Sun than Uranus, and a planetesimal disk extending up to ∼30–35 AU (Tsiganis et al. 2005) – see figure 2. By scattering planetesimals, Jupiter slowly drifts inward while other planets drift outward. After a few hundred Myr, Jupiter and Saturn cross their MMR, their eccentricities increase and the whole system is rapidly destabilized. Compact system gets chaotic orbits. This results in re-arrangement of planets and scattering of planetesimals, some of which reach inner solar system resulting in a cratering spike (LHB) ∼700 Myr after planets formed – consistent with observations. In about a hundred Myr the giants reach their current orbital positions (Crida 2009).

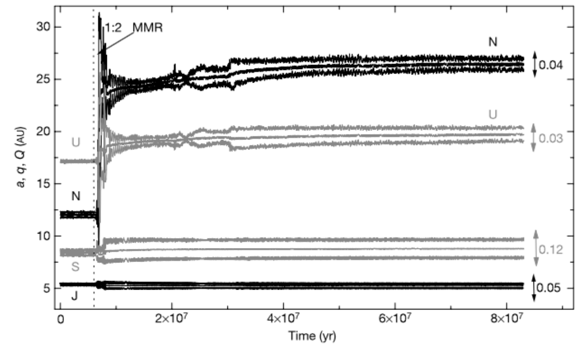

Figure 2. Orbital evolution of the giant planets – Nice model. Three curves are plotted for each planet: the semimajor axis (a) and the minimum (q) and maximum (Q) heliocentric distances. U, Uranus; N, Neptune; S, Saturn, J, Jupiter. (Tsiganis et al. 2005).

In the domain of terrestrial planets we must address additional problems, such as the reason Mars' mass is only $\approx 0.1 M_{\oplus}$, or why there are no planets at <0.4 AU? Informally titled "The Grand Tack" model (TGT) proposed by Walsh et al. (2011) explains this via rapid inward and outward migration (tacking) of Jupiter and Saturn on a time scale as short as ∼100 Kyr, before the times of the Nice model. The TGT model starts with a Jupiter fully formed at the most likely place – the snow line (3.5 AU), undergoing inward type I migration. Saturn formed later at 4.5 AU and migrated inwards faster, eventually catching up with Jupiter as close to the Sun as ∼1.5 AU, locking with Jupiter in a 2:3 MMR and reversing the migration of both planets, setting them on a course to where the Nice model initiates. This tacking of giants leads to a compressed and truncated inner disk of planetesimals from which terrestrial planets eventually form. Recent simulations by Batygin & Laughlin (2015) show that it also drives all the short-period protoplanets into the Sun. Earth and Venus grew within 0.7–1 AU while Mars had to collect the remainders of material on the outskirts of the disk, and this explains its unusually low mass. TGT simulations predict that tacking first empties and then repopulates the asteroid belt. Migrating giants shepherd S-type asteroids inwards by resonant trapping, eccentricity excitation and gas drag into the inner planetesimal disk where terrestrial planets have formed. The subsequent outward migration then scatters C-type asteroids from 8–13 AU into the outer portions of the asteroid belt, which is consistent with our observations of asteroid populations. This scenario represents a paradigm shift in our understanding of how asteroids have formed, suggesting C-type asteroids originate in and between the giant planets, closer to comets, while S-type asteroids are native to the inner portions of the solar proplyd. This is consistent with our observations of C-type asteroids having similarities with comets (Gounelle et al. 2008). Assuming C-type planetesimals are made of 10% water, and that scattering must have catapulted some into the inner portion of the early solar system, the TGT also provides us with a viable origin of water on Earth.

Looking at times even before the TGT, observational evidence points to that the formation of the solar system has started with an abundance of short-lived radionuclides (SRs), such as ^{26}Al and ^{60}Fe, most probably inherited from the interstellar medium (Gounelle & Meibom 2008). In the innermost parts of the solar proplyd—where terrestrial planets were formed—this has lead to the first generation of planetesimals rich in SRs (Morbidelli et al. 2012) which have collided, melted and differentiated (separated their different chemical constituents into distinct layers) due to nuclear decay heat. Terrestrial planets embryos emerging in this region of the proplyd induced SR-rich planetesimals to collide and fragment into stony and iron meteoroids and scatter out to the inner areas of the main asteroid belt, producing a population of S-type asteroids.

4. CONCLUSIONS

With Nice and TGT models, significant progress has been made in our understanding of the solar system formation and evolution. A good overview of the current state is available from Morbidelli et al. (2012). There are still problems, with the classic Nice model for example. The LHB it predicts will result in too many craters and basins on the Moon (Marchi et al. 2012). It is at odds with observations of ice on giant planets' satellites (Nimmo & Korycansky 2012) and the number of asteroid families (Brož et al. 2013). Initial conditions have also been tuned to produce MMR crossing around the time of LHB. An update to the model (Nice 2.0) is proposed that is based on a better fit to the empirical constraints and relieve some of the initial pre-requisites (Levison et al. 2011). Other proposals include 1–2 additional giants in the initial configuration of the system (Nesvorný & Morbidelli 2012). All the scenarios proposed may appear overly catastrophic, however they are consistent with our observations compatible with highly volatile and dynamic planet formation environments, as indicated by, for example, free-floating planets and giant exoplanets in a rich variety of orbits around other stars. Our future observations must be focused on testing our models and relieving them from poorly understood preconditions. High-resolution observation of proplyds on various evolutionary stages and exoplanets on *ALMA* or *JWST*, as well as observations of asteroids and comets will most certainly provide us with a wealth of additional information to work with.

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