Planetary Geological Formation

Tim B Perry
Paul Kenneth Seidelmann

Department of Astronomy
University of Virginia, Charlottesville, VA 22904, USA

This thesis is submitted in partial completion of the requirements of the BA Astronomy Major. May 9, 2019.

Abstract

These past semesters have been focused on researching newer models of planetary system evolution using the solar system as an analog. Observed planetary systems are skewed by what can be observed using current technology and methodology – as a result, they are largely ignored when modeling the solar system's formation. Instead, current understanding stems from simulations (which are also technologically limited) made to better understand the evolution of the solar system and the bodies within. In researching the topic, the (currently) accepted models are presented along with their shortcomings. The characteristics of bodies in the solar system are also detailed and the models in which they may form have been reviewed for plausibility. In most cases, there's still much to be desired and models are likely to change with future observations (particularly future missions to the outer solar system).

1. Introduction

In the last twenty years, from technological advancements and observations of the outer solar system, many hypotheses and models have been engineered (with better efficacy) to best explain what has been observed (in the solar system). In response to the newer data, many of the previous hypotheses have been refined to agree with newer observations, or put aside. This is an expected result, as there are still many unknowns in the formulation of a precise model of the solar system's formation and evolution. This includes (but is not limited to): the formation of the accretion disk around the proto-Sun, the distribution of material in the disk (with respect to distance from the proto-Sun), formation of planetary bodies, the evolution of these bodies since formation, and concerns raised from observations of exoplanetary systems. The explanation for each can be found amongst the competing literature, of which there are many, and vary in their complexity. As a general rule, simpler explanations are more likely to be correct than the complex counterparts (Occam's Razor), though the complexity of the field requires complicated modeling.

2. Planetary System Formation

The initial stages of planetary system formation are widely observed (telescope imaging of exoplanetary systems) and helped advance early formation models. From observations, the matter falling into a proto-star flattens into an accretion disk, compacted in the plane perpendicular to the proto-star's rotational axis, and spinning in the same direction as the proto-star rotates (as described by conservation of angular momentum). However, the formation and behavior of the gas surrounding proto-stars is not well understood (as it's difficult to observe). In many planetary formation models, the presence of this gas is usually minimized or ignored entirely. The inclusion of this gas envelope greatly over-encumbers the simulation, requiring far stronger computing power than is desired (or feasible). Of equal importance, the gas inclusion adds a prodigious complexity to the simulation – which can easily introduce chaos (a minor change may introduce instability into the model which spirals out of control). Though it is largely ignored (in simulations), the presence of gas in the early solar nebula may play a crucial role in the formation of planetary systems. Particularly in the migration of matter through the early stages of planetary formation – when the gas is still present. The gas, in developing planetary systems, acts to slow down matter passing through it (whether dust grain or planet) and promotes inward migration as the orbiting matter loses tangential velocity. This migration may lead to a variety of planetary distributions, but there is an inherent compositional distribution determined by the temperature (which changes with respect to radius from the star).

In the early solar system, as the surrounding accretion disk cooled, elements began condensing at well understood temperatures (determined by lab research). Two groups of elements, refractory (heavy) and volatile (light), condense at fairly well-defined radii from the proto-Sun due to the reduction in temperature with distance from the Sun and the relative condensation temperatures of the elements in each group. Refractory elements, such as iron, condense at higher temperatures (closer to the proto-Sun) and constitute the majority of the elements in the terrestrial planets. Volatile elements, which notably form water, condense at lower temperatures (in the outer solar system) beyond a relative radius (as it changes over time) referred to as the frost line. The distribution of these elements is seen in the relative densities of bodies in the solar system. The terrestrial planets (Mercury, Venus, Earth, and Mars) have densities of ρ = 5.43, 5.24, 5.51, and 3.93 gcm^{-3} (respectively) while the outer planets (Jupiter, Saturn, Uranus, and Neptune) have ρ = 1.33, 0.687, 1.27, and 1.64 gcm^{-3} (respectively). This distribution is also seen in the Galilean Moons – which are thought to have formed in an accretion disk around proto-Jupiter (Ronnet et al., 2016). These moons, from closest to farthest: Io, Europa, Ganymede, and Callisto have ρ = 3.53 (similar to Mars), 3.01, 1.94, and 1.83 gcm^{-3}. Unlike these Galilean Moons, which are closer in density, the planets vary by a wide degree – caused by the aforementioned condensation temperatures of elements. Closer to the proto-Sun, the temperatures were much warmer and inhibited the condensation of volatiles. Beyond the frost line, more material was available for planetary formation (the combination of volatile and refractory elements). The availability of material, is thought to have allowed for the rapid growth of ~10 M_{Earth} bodies which could begin gas accretion prior to the proto-Sun's T Tauri phase (a pre-main-sequence phase which produces powerful stellar winds) (Lambrechts & Johansen, 2018).

The proto-Sun's evolution into the luminous T Tauri phase limits the timeframe for gas giant formation to approximately 3-10 My (Lambrechts & Johansen, 2018). While this window is small in astronomical terms, it requires formation models capable of rapidly producing the rock/ice core to allow adequate time for gas accretion up to a Jupiter-sized body. Pebble accretion, one of the leading models (alongside core accretion), can consistently produce these giant embryos (Lambrechts & Johansen, 2018). In this model, matter builds to cm-m sized pebbles which may then join to form larger bodies. Eventually, the largest of these begin to gravitationally attract nearby pebbles along its orbital path. This process rapidly forms giant cores capable of gas accretion – which begins slowly, but (given enough time) can transition to runaway gas accretion (Kretke & Levison, 2014). In the solar system, the four giant planets appear to have developed at different rates, with Jupiter beginning gas accretion first (assumed by its size compared to the other giants). Additionally, the relative density of the material in the accretion disk plays a key role. From observations of exoplanetary system formation, this density falls off at greater radii from the proto-star. This leads to uncertainties regarding Uranus and Neptune's formation, and whether they formed closer to the proto-Sun and migrated to their present location.

The formation of Uranus and Neptune in-situ seems unlikely with the T Tauri constraint. The Nice Model is regarded as one of the best hypotheses for the giant planet formation and has been updated several times since its initial publication. The Nice Model suggests: Uranus and Neptune formed closer to the proto-Sun (today they are ~19 and 30 au) and later migrated outward due to an instability caused by Jupiter and Saturn reaching a 2:1 mean-motion resonance

(Deienno et al., 2017b). Once this happens, the orbits of the outer planets are quickly destabilized which sends Uranus and Neptune out towards their current orbital radii and is thought to have scattered planetesimals leading to the Late Heavy Bombardment (LHB). The LHB serves (primarily) as an explanation for the observed surface features on the Moon – though newer data appear to disagree with prior notions of the LHB. Additionally, the Nice model instability accounts for the capture of Jupiter's Trojan asteroids (in the L_4 and L_5 Lagrange points) and the lacking population of trans-Neptunian objects (TNO) (Tsiganis et al., 2005). Though, as with all formation models, the Nice Model is not without its faults – e.g. the ad hoc initial planetary configuration (Deienno et al., 2017b). Also, while the Nice Model does not rely on it (to achieve the current orbits of the outer planets), the Jumping-Jupiter scenario (in which an additional ice giant is ejected by Jupiter) achieves results which are more consistent with the observations of the solar system (the probability of such an evolution was estimated to be approximately 6%) (Brasser et al., 2018). Additionally, the Jumping-Jupiter scenario creates an inner solar system more closely resembling that which is observed today.

3. Formation Models for the Inner Solar System

Modeling the inner solar system requires agreement with the surprisingly low mass of Mars ($M_{Mars} \approx .1\ M_{Earth}$), the depletion of the asteroid belt, and the radial mixing of asteroids within the belt [seen by the co-existence of E (high albedo asteroids, rare outside of the inner belt), S (anhydrous and of siliceous composition, originating closer to the Sun) and C (carbonaceous, very low albedo - concentrated in the outer belt) type asteroids in the main belt] (Jacobson & Morbidelli, 2014). There are several models which achieve results similar to these, all of which require a truncated system creating an annulus with an outer edge around 1 au (Deienno et al., 2017a). (Walsh & Levison, 2016) arrived at such a system (though it was not one of the goals of the study) by modeling the formation of the inner planets from cm-sized pebbles via pebble accretion. Unlike this, the Grand Tack model was developed to explain the aforementioned characteristics of the inner solar system, namely Mars and the asteroid belt. The Grand Tack model describes the inward migration of Jupiter to ~1.5 au via type II migration (which occurs when a giant planet sufficiently clears the gas in its orbital path) - a process which also explains the phenomena of Hot Jupiters (approximately Jupiter sized exoplanets orbiting within the relative distance from Earth to the Sun – dependent on the star's characteristics). This migration effectively starves the region and creates the desired annulus up to ~1 au – leading to the extant low mass Mars which older (disproven) models expected to be much larger (Raymond et al., 2009). Saturn being smaller at this time, likely having formed farther from the Sun, started its migration after Jupiter, but migrated more quickly via type I migration (where smaller planets migrate via torques generated from waves at the Lindblad resonance) (Walsh et al., 2011). Their inward migrations continued until Jupiter and Saturn reached a 3:2 mean-motion resonance and began outward migration – which may have ended due to the dissipation of the gas disk (D'Angelo & Marzari, 2012). During the inward migration, Jupiter pushes most of the inner (S-type) asteroids to smaller orbital radii – though approximately 10% of these are scattered out to orbits of 4-10 au (Walsh et al., 2011). On Jupiter and Saturn's migration to the outer solar system, they scatter a fraction of a percent of C-type bodies into the asteroid belt (Walsh et al., 2011). While the Grand Tack model seems best at creating the observed characteristics of the inner solar system, it's not without fault. Namely, the observed maximum eccentricity of asteroid belt objects is approximately 0.1, while the Grand Tack model ends with a more excited asteroid belt (max eccentricity of approximately 0.4) (Morbidelli et al., 2016). Recently however, separate studies by (Deienno et al., 2017a) and (Roig & Nesvorny, 2015) found the post Grand Tack asteroid belt could evolve to the observed configuration. Currently, there is no single model which accounts for all parts of the observed Solar System – though the answer may be a combination of those presented. Additionally, there is still much to be discovered and understood – particularly in the outer Solar System, where ground-based observation is limited by the absence of light and spacecraft observation is limited by the time spent in the outer solar system.

4. Terrestrial Planet H_20

There are also observed characteristics on the terrestrial planets and outer solar system satellites which raise their own problems – such as the abundance of water on Earth. Currently, there are two primary hypotheses to account for the presence of water on Earth – both of which seem unlikely to be the sole deriver. First, the possibility that Earth's water was delivered by comets from the outer solar system. Detections of (what seems likely to be) water ice in polar craters of Mercury and the Moon may also support this method – though water delivered via other methods would be expected to gather where sustainable. In conjunction with crater dating on the Moon, a late instability (~800 My after the solar system's formation) may have sent outer solar system bodies (containing volatiles) into the inner solar system. A scenario which is described by the Nice Model. The Grand Tack model also describes the possible delivery of water rich embryos from the outer solar system. In a review of the Grand Tack model, Raymond and Morbidelli found the inner embryos (those of the inner solar system and devoid of water) are outnumbered by the outer (water rich) embryos by approximately an order of magnitude (Raymond & Morbidelli, 2014). With this in mind, they conclude that this could account for Earth's current water abundance, a notion presented earlier by (Walsh et al., 2011) and (O'Brien et al., 2014). The second describes Earth's water budget coming from within via volcanic outgassing. Initially, volatiles (including Hydrogen and Oxygen) were trapped in the Earth's interior. Over time, these gasses were released to create the Earth's atmosphere (note, the extant O in the atmosphere was created via photosynthesis, not by this outgassing). In 2014, the ESA's Herschel space observatory found water vapor near Ceres. From later observations from DAWN, the vapor likely came from sublimating ice on the surface, which may have been ejected from Ceres' interior (though the DAWN mission leaves much to be desired). While the source is unknown, the longevity of Earth's water inventory appears to be its unique aspect.

At ~1.5 au, observations of the Martian surface point to a history of water – though the exact timescale is controversial. Ongoing observations on Mars (such as the Curiosity Rover) have uncovered clear indications (such as smoothed pebbles in craters) of ancient flowing water. Additionally, it's unclear whether the water existed as lakes and oceans or if the water erosion features came from a rapid period of flooding. In the earlier stages of the solar system's evolution, the temperature was greater at Mars's orbital radius. Additionally, Mars still had an active core – the exact timeline for the Martian interior is skeptical, although observations from Olympus Mons and the volcanoes in the Tharsis region indicate fairly recent volcanic activity (around 260 Mya, though some estimate more recent activity) (Berman & Crown, 2019). An active core likely formed a magnetic field which may have protected an early (denser) Martian atmosphere, possibly increasing the surface temperature via the greenhouse effect. In such a scenario, liquid water may have collected on the Martian surface. Alternatively, subsurface water may have existed as large collections of ice, which were subsequently heated (likely from nearby magma intrusions) causing large scale flooding on the surface (Cassanelli & Head, 2019). Today, with a (thought to be) solidified core and thin atmosphere (~0.6 of Earth's), water exists on Mars as subsurface ice and polar ice (alongside CO_2 ice). The other terrestrial planets (Mercury and Venus) are too hot to support large inventories of volatiles (though it's possible Venus contained water prior to entering a runaway greenhouse effect).

5. Terrestrial Atmospheres and Volcanic Activity

A terrestrial planet's ability to develop and maintain a substantial volatile inventory is tied to its distance from the Sun and subsurface activity (both of which contribute to atmospheric viability). Mercury, ~0.4 au from the Sun (though fairly eccentric, $e \approx 0.2$), is too close to the Sun (surface temp reaching ~700 K in direct sunlight) to have likely ever maintained an atmosphere or harbor a substantial water inventory. Though it was volcanically active in its past (inferred from observed remains of explosive volcanism). Approximately 0.3 au farther from the Sun, Venus may have once had a similar inventory of volatiles as Earth (often considered sister planets). While observations of Venus are more difficult, due to the dense atmosphere (~9.3 MPa or ~93 times the mass of Earth's atmosphere) and a ubiquitous surface temperature ~655 K, the Venusian surface is much younger than expected (from comparing crater density to elsewhere in the solar system – of note: only bolides capable of creating >~ 3 km craters make it to the surface) (Bougher et al., 1997). Also, Venus has a substantial record of volcanism (which likely outgassed a substantial inventory of volatiles – in addition to the extant $C0_2$). All of which has been created with an apparent lack of tectonic plates (a geologic phenomenon which appears to be unique to Earth – though similar processes may have occurred in the ice sheets of Europa). Approximately 0.3 au farther still, Earth has evolved to maintain a substantial inventory of volatiles (with respect to the other terrestrial planets). However, rather than reviewing its characteristics, Earth is used for comparison (though less convincingly when compared to bodies of vastly different formational parameters – e.g. outer solar system moons). Of note, its internal heat, and subsequent volcanic activity, is generated by the radioactive decay of the heavier internal elements (though additional heat sources contribute – e.g. early accretion). In the evolution of complexity on solid bodies, prolonged heat generation appears to play a key role – which is evident when comparing the moons of the outer solar system. All of the terrestrial planets show a history of prolonged volcanic activity which stems from their composition (mostly silicates and metal – refractory elements) and reflected in their densities ($\rho_{Mercury} = 5.43$, $\rho_{Venus} = 5.24$, $\rho_{Earth} = 5.51$, $\rho_{Mars} = 3.93$ gcm^{-3}). Alternatively, internal heat can be generated from tidal interactions – such as on Io.

6. Terrestrial Planet erosion and Volcanic formations

Weather (though only seen on Earth and Mars – when considering the terrestrial planets) in combination with the aforementioned volcanic viability have led to significant surface differences on the terrestrial planets. Mercury is thought to have become inactive ~3.5 Gya and lacks any signs of additional erosion (unsmoothed crater edges) – though there is evidence of past pyroclastic volcanism in explosive vents (Klimczak et al., 2018). Similar volcanic eruptions occur on Earth and are caused by the inclusion of volatiles in the source magma [the intermixing of volatiles within Mercury (causing the pyroclastic volcanism) supports the hypothesized contribution of outgassing on Earth]. In addition to these explosive vents, Mercury has many scarps which were likely formed as Mercury's crust contracted during cooling (Barlow & Banks, 2018). Venus has a wide variety of volcanic features (such as: lava channels, compressional (ridges) and extensional tectonics (grabens), shield volcanoes (which are present in several sub-classes), calderas, and more) caused by hot spot volcanism (like the Hawaiian Islands). As a result of this extensive volcanism, Venus developed its dense CO_2 atmosphere, though (because of its composition) the Venusian surface lacks appreciable wind erosion – though wind streaks can be seen around volcanic cones. Mars has also experienced a great deal of volcanic activity in its past, though most of it occurred in one cluster – the Tharsis region. As on Venus, the Martian volcanoes are shield volcanoes caused by hot spot volcanism. Due to their immense size (Olympus Mons, the largest - though just outside of the region, extends ~21.3 km from the surface) hot spots likely began creating these volcanoes soon after Mars' surface cooled (and have remained localized). Unlike Mercury and Venus, the Martian surface experienced significant erosion – a history preserved in the degradation of craters (some craters almost entirely erased – and likely some which have been completely erased). Water almost certainly eroded parts of the surface earlier in Mars's history (seen in the rounded sediments in craters), but currently eolian forces are the only erosional phenomenon (observed on Mars). Eolian activity is actively seen on Mars (at times the surface is visually shrouded by dust storms) along with formations caused by repeated exposure to winds (e.g.: sand dunes, spiral/swirl formation at the North Pole, dust devils, ventifacts, and yardangs).

7. Outer solar system conditions

The bodies (satellites of giant planets and Pluto) of the outer solar system are primarily composed of volatiles – with the exception of Io. As such, the mechanism which generates (volcanic/cryovolcanic) activity is caused by an alternate source – such as tidal forces. These outer moons also lack atmospheres which may be in part due to the body's size, temperature, and or (internal) inactivity – though Titan is an exception. It is also important to consider the change in elemental and molecular characteristics with greater distances from the Sun. For instance, the strength/rigidity of water ice throughout the solar system. On Jovian moons, the water ice is far less rigid than on Pluto, where water ice has formed mountainous regions (though this conclusion is somewhat speculative). In a similar fashion, volatiles may be in a gaseous or solid state depending on the location at which it is observed. At Titan, nitrogen gas makes up ~98% of its atmosphere, but exists as a solid on Triton and Pluto. Lastly, in modeling the giant planet systems, it's important to consider whether the moons were formed in-situ, or possibly captured (which appears the case for Triton).

8. Jovian/Galilean Moons

In modeling the Jovian system, the relative densities of the Galilean moons [ρ_{Io}, ρ_{Europa}, $\rho_{Ganymede}$, and $\rho_{Callisto}$ = 3.53, 3.01, 1.94, and 1.83 gcm^{-3}] suggest an in-situ formation from a subnebula around early Jupiter (Ronnet et al., 2016). This density gradient suggests the Jupiter subnebula developed in an analogous way to the solar system as a whole – with greater temperatures in the interior leading to denser bodies with lower volatile inventories. The innermost and densest moon, Io (~4.2×10^5 km from Jupiter), is the most volcanically active body in the solar system. There's still much to be desired regarding its interior characteristics (as is the same for all the bodies in the solar system), though its surface appears to undergo perpetual rejuvenation (assumed by its nearly craterless surface), which requires an energetic interior. In the case of Io, and Europa to a lesser extent (as $F_{\text{tidal}} \propto \frac{1}{r^3}$), the interior is heated via tidal interactions with Jupiter, and persists due to resonance with the other Galilean moons (a 4:2:1 orbital resonance between Io, Europa, and Ganymede). If this resonance was not present, the moons would fall into tidally locked circular orbits (such as the Moon) and would lack the energy required for volcanic/cryovolcanic activity (though cryovolcanic activity can be stimulated by sunlight). The volcanic activity on Io has been seen as eruptions in paterae (surface depressions in Io's surface) and explosive eruptions (some of which were imaged by New Horizons). Unlike terrestrial volcanism, Ionian volcanism does not form volcanic highlands (such as shield volcanoes) and apparently lacks plate tectonics seen on Earth (though thrust faulting is present due to contraction). Europa, ~2.5×10^5 km farther from Jupiter than Io, appears to be inactive on its surface (though possible plumes were detected by the Galileo probe). However, Europa's surface is covered by lineae (cracks such as triple bands) which may have acted similar to oceanic ridges on Earth (though the desire to draw connections may outweigh the accuracy of this hypothesis) (Greeley et al., 1998). The widespread and discontinuous nature of the surface features complicates hypotheses explaining its formation. If the ice crust is, or was, disconnected from the interior rocky core by a liquid ocean, the larger cracks may have formed by tidal kneading as the outer layer spun freely (though this hypothesis seems less likely) (Ronnet et al., 2016). Or perhaps, in addition to smaller features, all of the surface features seen were formed via cryovolcanic activity when Europa's interior was warmer (earlier in its history) (Kargel et al., 2000). This hypothesis is supported by what's seen on Ganymede. As the third farthest Galilean moon, with respect to Jupiter (~4×10^5 km farther than Europa), far less energy is generated from its orbital motion and is evident in its lacking surface features (relative to Europa). Its surface is covered by ancient (darker) regions of ice, which formed early in its history, intermittently interrupted by bright regions where fresher material has been exposed by cratering. Overtime, craters on Ganymede are relaxed and form palimpsests (also observed on Callisto), or circular regions brighter than their surroundings which no longer resemble craters. Even farther from Jupiter, Callisto shows the oldest surface (having a denser cratering record than Ganymede), but lacks the widespread history of surface activity seen on the other Galilean moons.

9. Saturnian Moons

The Saturnian system is also thought to have formed from a subnebula, though the system as a whole formed farther from the Sun than Jupiter and early Saturn's lower luminosity would've formed a shallower gradient (the reduced density as a function of distance from the host body). Out of the many Saturnian Moons, Enceladus and Titan show interesting characteristics and continued activity. Enceladus (~2.4×10^5 km from Saturn), is the only icy moon to be observed ejecting material from its interior (though Europa may also produce plumes). Analogous to Io, the interior of Enceladus is thought to be heated by tidal interactions with Saturn due to a resonant orbit (2:1) with Dione. With recent observations from Cassini, Enceladus was observed ejected plumes (primarily composed of H_20) from geysers in its South Polar Terrain (SPT) (Waite et al., 2011). During Cassini's time at Saturn, thermal imaging of the SPT detected raised temperatures within the individual depressions of the Tiger Stripes (TS) (near-parallel depressions in the SPT). From the combination of these observations, the TS are found to be the source of the emitted material replenishing Saturn's E ring, confirming early hypotheses. Its activity is also seen on Enceladus' surface, as the SPT has far fewer craters than the Northern Hemisphere (having been filled by ejected material). Unlike the other moons of the outer solar system, there is direct evidence of subsurface water on Enceladus, though the extent of the source is unknown. Farther from Saturn, ~10^6 km farther than Enceladus, Titan maintains a dense nitrogen rich atmosphere. Though it's not understood how Titan developed and has kept its atmosphere, the presence of methane suggests a replenishment mechanism – or a fairly recent introduction of methane into the system. Over time, the methane and molecular nitrogen in the atmosphere are converted into hydrocarbons (tholins) which fall to the surface, slowly depleting the atmosphere's methane inventory (Cordiner et al., 2017). There's still much to be learned about Titan's surface, though radar imaging has uncovered surface features and other unique phenomena (as compared to the other outer satellites). Analogous to Earth's water cycle, Titan is subject to a methane cycle which has eroded the surface and created lakes of methane (Dunbar, 2013). Also, recently, evidence of a dust storm was found from analysis of older Cassini data.

10. Triton and Pluto

Triton is Neptune's largest satellite and was likely captured as it is in a retrograde orbit around Neptune. This is not to say prograde satellites are therefore formed in-situ. Rather, conservation of angular momentum suggests the satellite should orbit in the same direction as the host planet's rotation, should it have formed as part of the system. Triton orbits ~3.5×10^5 km from Neptune, but has an eccentricity of 1.6×10^{-5} – much smaller than Io (0.0041), Europa (0.009), or Enceladus (0.0047). At present, the only in-situ observations of Triton come from the Voyager 2 flyby in 1989 (Spohn et al., 2014). From these data, Triton has a surface composition of ~55% N ice, 15-35% H_20 ice, and 10-20% $C0_2$ ice (with some trace ices- e.g. CH_4) (Spohn et al., 2014). Triton also has interesting surface features (bumps and depressions nicknamed cantaloupe terrain) and a relative lack of cratering (unsaturated). Due to its retrograde motion and similar composition with Pluto, there's a hypothesis in which they share an origin – though the evidence for this is (beyond the compositional similarity) sparse (Encrenaz et al., 2004).

Pluto's distance from the Sun ranges from ~30 au (the same as Triton) to ~40 au and its surface activity is thought to vary seasonally (as with Triton) (Cordiner et al., 2017). Notably, Sputnik Planitia (SP), a region of N_2 ice surrounded by H_20 highlands, was craterless (as observed by New Horizons) and contains (what's thought to be) convective cells of ice (McKinnon et al., 2016). Within these cells exist sublimating pits (similar to sublimation patterns on Mars' south pole). Pluto also has methane dunes west of SP, thought to have formed from winds coming off SP (Telfer et al., 2018). Its companion, Charon – to which it is tidally locked, is proportionally larger to Pluto than the Moon to Earth ($R_{Charon} \approx \frac{1}{2} R_{Pluto}$; $R_{Moon} \approx \frac{1}{6} R_{Earth}$). The pair, along with the small Plutonian satellites, are thought to be the product of a collision – similar to the Earth Theia hypothesis. Charon's north polar region is covered by tholins created on Pluto which are thought to gradually find their way to Charon (Grundy et al., 2016). Most notably, near the equator of Charon, there is a set of fractures (the source for which is controversial) with younger (smoothed) material southward – possibly indicating past cryovolcanic activity.

11. Conclusion

Instrumentation such as TESS (and future space telescopes) will allow more accurate models – some of which will likely disprove current hypotheses (as has happened in the past). Despite the uncertainties, the general structure of planetary systems seems fairly well understood – though Kepler data suggests the solar system is an oddity (largely due to technological constraints). As the system forms, there is an initial gradation of elements with respect to the proto-star that forms bodies of differing compositions (dependent on the distance of formation). Beyond this, the current sample size is too low to draw conclusions regarding characteristics of planetary systems as a whole.

Models of the solar system's formation and evolution will continue to change with newer observations (particularly those of bodies in the outer solar system). These bodies have only recently been observed with greater detail, and only by up to a few probes – leaving much to be desired. The outer bodies are also subject to changes depending on the season in which they are observed (which take years to change) and requires an even greater observation time to understand the fluctuations. The exact model for the solar system, including the evolution of the bodies within, may never be understood perfectly, but continued observation and better technology will allow the formation of hypotheses which more closely resemble its true evolution.

12. References

Barlow, N. G., Banks, M. E. 2018. Constraints on the timing of tectonic activity on Mercury's large-scale lobate-scarp thrust faults. LPI Contrib. No. 2047.

Berman, D. C., Crown, D. A. 2019 Chronology of Volcanism in Southern Tharsis, Mars… 50th Lunar and Planetary Science Conference 2019.

Bougher, S. W., Hunten, D. M., Philips, R. J., et al. 1997. Venus II – Geology, Geophysics, Atmosphere, and Solar Wind Environment. University of Arizona Press

Brasser, R., Morbidelli, A., Gomes, R., Tsiganis, K., Levison, H. F. 2018. Constructing the secular architecture of the solar system II… Astronomy & Astrophysics 507, 1053- 1065

Cassanelli, J. P., Head, J. W. 2019. Glaciovolcanism in the Tharsis volcanic province of Mars: Implications for regional geology and hydrology. Planetary and Space Science 169, 45-69

Cordiner, M. A., Lai, J. C., Teanby, N. A., et al. 2017. ALMA observations of Titan's Atmospheric chemistry and seasonal variation. IAU Symposium No. 332.

D'Angelo, G., Marzari, F. 2012. Outward migration of Jupiter and Saturn in evolved gaseous disks. The Astryophysical Journal, 757:50.

Deienno, R., Gomes, R. S., Walsh, K. J., Morbidelli, A., Nesvorny, D. 2017. Is the Grand Tack model compatible… Icarus 272, 114-124.

Deienno, R., Morbidelli, A., Gomes, R. S., Nesvorny, D. 2017. Constraining the Giant Planets' Initial Configuration… The Astronomical Journal. 153:153.

Dunbar, B. 2013. Cassini Shapes First Global Topographic Map of Titan. NASA.gov. web. 2019

Encrenaz, T., Kallenbach, R., Owen, T.C., Sotin, C. 2004. The Outer Planets and their Moons. Springer.

ESA. N.D. Herschel discovers water vapour around dwarf planet Ceres. Esa.int. Web. 2019.

Greeley, R., Sulivan, R., Klemaszewski, J., et al. 1998. Europa: Initial Galileo Geological Observations. Icarus 135, 4-24.

Grundy, W. M., Cruikshank, D.P., Gladstone, G. R., et al. 2016. Formation of Charon's Red Poles from Seasonally Cold-Trapped Volatiles. Nature 539, 65-68.
Hauber, E., Broz, P., Jagert, F., Jodlowski, P. Platz, T. 2011. Very recent and wide-spread basaltic volcanism on Mars. Geophysical Research Letters 38, L10201.
Jacobson, S. A., Morbidelli, A. 2014. Lunar and Terrestrial Planet Formation in the Grand Tack Scenario. R. Soc. A 372: 20130174.
Jewitt, David, Chizmadia, Lysa, Grimm, Robert, Prialnik, Dina. 2006. Water in Small Bodies of the Solar System. University of Hawaii.
Kargel, J. S., Kaye, J. Z., Head, J. W. III, et al. 2000. Europa's Crust and Ocean: Origin, Composition… Icarus 148, 226-265.
Klimczak, C., Crane, K. T., Habermann, M. A., Byrne, P. K. 2018. The spatial distribution of Mercury's pyroclastic activity .... Icarus 315, 115-123.
Kretke, K. A., Levison, H. F. 2014. Challenges in forming the solar system's giant planet Cores… The Astronomical Journal, 148:109.
Lambrechts, M., Johansen, A. 2018. Rapid growth of gas giant cores by pebble accretion. A & A 544. A32
Levison, H. F., Dones, L., Chapman, C. R., Stern, S. A., Duncan, M. J., Zahnle, K. 2001. Could the "Late Heavy Bombardment" Have Been Triggered by the Formation of Uranus and Neptune? Icarus 151, 286-306
McCartney, G. 2018. Dust Storms on Titan Spotted for the First Time. Jpl.NASA.gov. web 2019
McKinnon, W. B., Francis, N., Wong, T. et al. 2016. Convection in a volatile nitrogen-rich.... Nature 534, 82-85.
Morbidelli, A., Walsh, K.J., O'Brien, D.P., Minton, D. A., Bottke, W.F., 2016. The Dynamical Evolution of the Asteroid Belt. in Asteroids IV, University Arizona Press
Nesvorny, D., Vokrouhlicky, D., Deienno, R. 2014. ApJ,784, 22
O'Brien, D. P., Walsh, K. J., Morbidelli, A., Raymond, S. N., & Mandell, A. M. 2014. Water delivery and giant impacts in the 'Grand Tack' scenario. Icarus 239, 74
Raymond, S. A., Morbidelli, A. 2014. The Grand Tack model: a critical review. IAU Symposium 310, 194-203.
Raymond, S. N., O'Brien, D. P., Morbidelli, A., Kaib, N. A. 2009. Building the terrestrial planets: Constrained accretion in the inner Solar System. Icarus 203, 644-662.
Roig, F., Nesvorny, D. 2015. The Evolution of Asteroids in the Jumping-Jupiter Migration Model. The Astronomical Journal 150, 186.
Ronnet, T., Mousis, O., Vernazza, P. 2016. Evolution of solids in the Jovian subnebula: Implications for the formation of the Galilean satellites. SF2A 2016.
Spohn, T., Breuer, D., Johnson, T. 2014. Encyclopedia of the Solar System (3rd ed.). Amsterdam; Boston: Elsevier.
Telfer, M. W., Parteli, E. J. R., Radebaugh, J., Beyer R. A., Bertran et al. 2018. Dunes on Pluto. Science 360, 992-997.
Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H. F. 2005. Origin of the orbital architecture of the giant planets of the Solar System. Nature 435, 459-469.
Waite, J. H., Magee, B., Brockwell, T., Zolotov, M. Y., Teolis, B., Lewis, W. S. 2011. Enceladus Plume Composition. EPSC Abstracts 6, EPSC-DPS2011-61-4.
Walsh, K. J., Levison, H. F. 2016. Terrestrial Planet formation from an Annulus. The A. J. 152:68
Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P., Mandell, A. M. 2012. A low mass

for Mars from Jupiters early gas-driven migration. Nature 475, 206-209.