

ORIGIN OF EARTH'S WATER: SOURCES AND CONSTRAINTS

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The origin of Earth's water is a longstanding question in the fields of planetary science, planet formation and astrobiology. In this chapter we review our current state of knowledge. Empirical constraints on the origin of Earth's water come from chemical and isotopic measurements of solar system bodies and of Earth itself. Dynamical models have revealed potential pathways for the delivery of water to Earth during its formation, most of which are anchored to specific models for terrestrial planet formation. Meanwhile, disk chemical models are focused on determining how the isotopic ratios of the building blocks of planets varied as a function of radial distance and time, defining markers of material transported along those pathways. Carbonaceous chondrite meteorites – representative of the outer asteroid belt – provide a good match to Earth's bulk water content (although mantle plumes have been measured at a lower D/H). What remains to be understood is how this relationship was established. Did Earth's water originate among the asteroids (as in the classical model of terrestrial planet formation)? Or, more likely, was Earth's water delivered from the same parent population as the hydrated asteroids (e.g., external pollution, as in the Grand Tack model)? We argue that the outer asteroid belt – at the boundary between the inner and outer solar system – is the next frontier for new discoveries. The outer asteroid belt is icy, as shown by its population of icy bodies and volatile-driven activity seen on twelve main belt comets (MBCs); seven of which exhibit sublimation-driven activity on repeated perihelion passages. Measurements of the isotopic characteristics of MBCs would provide essential missing links in the chain between disk models and dynamical models. Finally, we extrapolate to water delivery to rocky exoplanets. Migration is the only mechanism likely to produce very water-rich planets with more than a few percent water by mass (and even with migration, some planets are purely rocky). While water loss mechanisms remain to be studied in more detail, we expect that water should be delivered to the vast majority of rocky exoplanets.

1. INTRODUCTION

We have only one example of an inhabited world, namely Earth, with its thin veneer of water, the solvent essential to known life. Is a terrestrial planet like Earth that lies in the habitable zone and has the ingredients of habitability a common outcome of planet formation or an oddity that relied on a unique set of stochastic processes during the growth and subsequent evolution of our solar system?

Ultimately, water originates in space, likely formed on dust grain surfaces via reactions with atoms inside cold molecular clouds (Tielens and Hagen 1982; Jing *et al.* 2011). Grain surface water ice then provides a medium for the chemistry that forms molecules of biogenic relevance (Herbst and van Dishoeck 2009). Both water and organics are abundant ingredients in protoplanetary disks out of which solar systems form. In the disk, water is present both as a gas and a solid and is likely processed during planet formation. The Earth formed in our solar system's inner protoplanetary disk. The sequence of events that led to the growth of a rocky Earth with a thin veil of water remain to

be fully understood. Both thermal processing – in particular, desiccation of the earliest generations of planetesimals due to ^{26}Al heating (Grimm and McSween 1993; Monteux *et al.* 2018; Alexander 2019a) – and Earth's orbital location within the planet-forming disk likely played important roles. Water only exists as ice past the disk's *snow line*¹ which itself shifts inward in time as the disk evolves, and which may have been located interior to Earth's orbit during part of Earth's formation. Reconciling Earth's water content with meteoritic constraints and models for Solar System formation remain a challenge.

While there has been significant work to investigate the origin of Earth's water—the wellspring of life—we still do not know if it came mostly from the inner disk or if it was delivered from the outer disk. No one knows if our solar system, with a planet possessing the necessary ingredients for life within the habitable zone, e.g. sufficient water and

¹the radial distance from the star beyond which the temperatures are low enough for gases to condense as ice

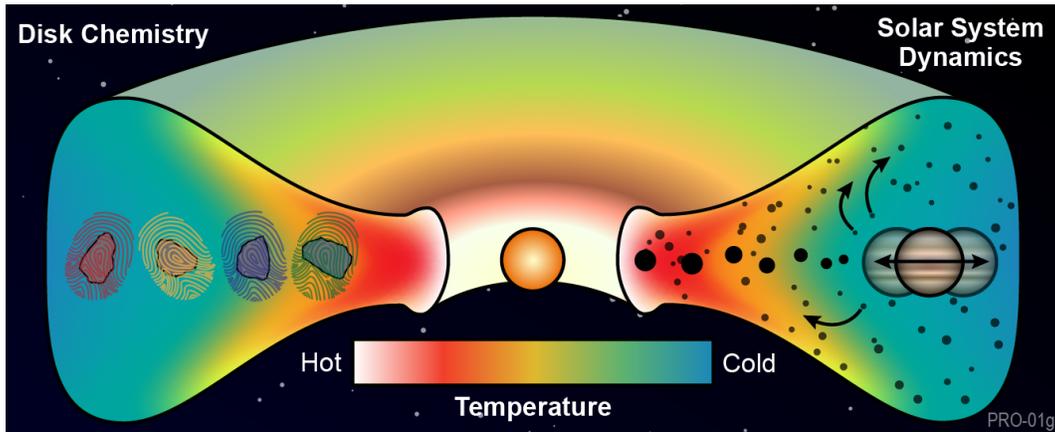


Fig. 1.— Protoplanetary disk chemical signatures are implanted on planetesimals as ices freeze near the midplane. This fingerprint is a sensitive measure of the planetesimal formation location. Subsequent planetesimal scattering as the giant planets grew will scramble this signature. The key to understanding where inner solar system volatiles originated is to measure the isotopes in a primitive reservoir of material that records the dynamical history during formation.

organics, is a cosmic rarity. Nor do we know whether the gas giants in our solar system aided or impeded the delivery of essential materials to the habitable zone. The answers to these questions are contained in volatiles² unaltered since the formation of the giant planets. To access this record, we need: (1) a population of bodies that faithfully records the history of volatile migration in the early solar system; (2) a source of volatiles that we can access; (3) knowledge that the volatiles were not altered by aqueous interaction with their parent body; and (4) measurements from multiple chemical markers with sufficient precision to distinguish between original volatile reservoirs.

Comets were long thought to be the most likely “delivery service” of Earth’s water based on a comparison of their D/H ratio’s with that of Earth’s ocean (Delsemme 1992; Owen and Bar-Nun 1995). But new models and data, including the *Rosetta* mission’s survey of comet 67P/Churyumov-Gerasimenko, have cast doubt on this source. The relative abundances of 67P’s volatile isotopes (D/H, N, C and noble gases) do not match those of Earth (Altwegg et al. 2015; Marty et al. 2016). Furthermore, comets will not provide an answer to the original source of Earth’s water because they are dynamically unstable and can not be traced back to where they formed (Levison and Duncan 1997; Brasser et al. 2013). The only way to learn where Earth’s water came from is to match the chemical fingerprints of inner solar system volatiles to a location in the protoplanetary disk. Such data can distinguish between competing models of solar system formation to specify where the water came from and how it was delivered.

Our solar system is quantifiably unusual compared to the thousands of known exoplanet systems (Martin and Livio 2015; Mulders et al. 2018; Raymond et al. 2018b). Af-

ter taking observational biases into account, only $\sim 10\%$ of Sun-like stars have gas giants (Cumming et al. 2008; Mayor et al. 2011; Fernandes et al. 2019), and only $\sim 10\%$ of outer gas giants have low-eccentricity orbits like Jupiter (Butler et al. 2006; Udry et al. 2007), putting the solar system’s orbital architecture in a $\sim 1\%$ minority (for a discussion, see Raymond et al. 2018b). Many exoplanetary systems have Earth-sized planets in or near their host star’s habitable zones (e.g., in the TRAPPIST-1 system; Gillon et al. 2017), and a handful of systems have outer gas giants and inner small planets (e.g., the Kepler-90 8-planet system; Cabrera et al. 2014). It remains unclear whether these planets are actually habitable. Liquid water is certainly a key ingredient, and it remains to be seen whether the solar system’s formation and the planetary arrangement itself were critical in setting the conditions needed for life, in terms of the quantity and timing of volatile delivery. However, it is important to ascertain the mechanisms for water delivery to the inner planets, as this is directly relevant to the habitability of those planets, and thus bears on the age-old question, “Are we alone?”

1.1. What we Know about Earth’s Water

The inner solar system is relatively dry (Abe et al. 2000; van Dishoeck et al. 2014). Mercury is dry except for surface ice seen at the poles, likely deposited from recent exogenous impacts (Deutsch et al. 2019). Venus was once wet (Donahue et al. 1982), but experienced major water loss through hydrodynamic escape or impact-driven desiccation (Kasting and Pollack 1983; Kurosawa 2015). Likewise, Mars may have once had significant water, but has also lost a large fraction of its atmosphere to space via sputtering (Jakosky et al. 2017). While images of Earth from space suggest that it is a black oasis in space, rich in water, the bulk Earth is in fact relatively dry. However, its pre-

²In planetary science volatiles are compounds that are typically found as gases or as ices in the outer solar system.

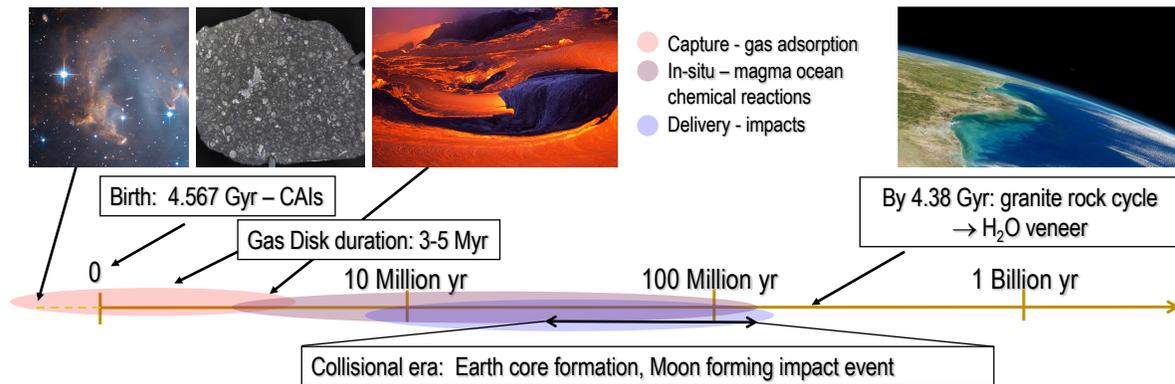


Fig. 2.— Earth received its water early; by 4.38 Gy Earth had oceans. Images from:ESA and the Hubble Heritage team (STScI/auRA)-ESA/Hubble Collaboration; AMNH-Creative commons license, 2.0 (<https://creativecommons.org/licenses/by/2.0/deed.en>); NASA.

cise water content is uncertain. Assessments of the amount of water stored as hydrated silicates within the mantle vary between roughly one and ten “oceans” (Hirschmann 2006; Mottl *et al.* 2007; Marty 2012; Halliday 2013), where one ocean is defined as the amount of water on Earth’s surface (by mass, roughly $2.5 \times 10^{-4} M_{\oplus}$). The amount of water in Earth’s core is also uncertain (Badro *et al.* 2014; Nomura *et al.* 2014), although recent laboratory experiments suggest that it is quite dry and that the bulk of Earth’s water resides in the mantle and on the surface (Clesi *et al.* 2018).

Earth’s water was incorporated during its formation. Planets form around young stars in disks of gas and dust, whose characteristics may vary (Bate 2018). Disks are $\sim 99\%$ gas by mass. The solid component of the disk starts as sub micron-sized dust grains inherited from the interstellar medium. Water is provided to the disk as ice coatings on grains. What is not clear is how much recycling of water there is in the disk. The disk is flared, i.e., the thickness of the disk increases with radius, so the disk top and bottom surfaces are exposed to radiation from the star. This heats the surfaces, producing a vertical variation in temperature (in addition to a general decrease in temperature with distance from the star), as shown schematically in Fig. 1. Matter is accreted from the disk onto the star, adding to the star’s UV and x-ray flux. This can alter water chemistry and isotopic composition as a function of position and time. Isotopes can preserve the signature of these kinds of disk processes and will be the key to tracing the volatiles in the early solar system.

Cosmochemical and geochemical evidence provides clues that Earth’s water arrived early (Fig. 2; see also the discussion in the chapter by Zahnle and Carlson). The condensation of the first solar system solids (the Calcium and Aluminum Inclusions; CAIs) sets the time “zero” for the birth of the Solar System at 4.567 Gyr (Amelin *et al.* 2002; Krot and Bizzarro 2009; Bouvier and Wadhwa 2010). As discussed in Section 3, it is believed that water could have arrived at Earth (1) locally as gas that was adsorbed onto the surface of dust grains (King *et al.* 2010; Asaduzzaman

et al. 2014), or (2) it could have formed on Earth’s surface if a magma ocean was in contact with a primordial hydrogen atmosphere (Ikoma and Genda 2006), or (3) water could have been dynamically delivered from the ice-rich outer solar system (Walsh *et al.* 2011a; Raymond and Izidoro 2017a). Both observations and models of protoplanetary disks show that the lifetimes of gaseous protoplanetary disks are very short, a few Myr (Haisch *et al.* 2001; Ercolano and Pascucci 2017), so local processes would have had to have occurred early. Likewise Earth’s magma ocean probably could have lasted anywhere from a hundred thousand years to more than ~ 100 Myr (Elkins-Tanton 2012; Hamano *et al.* 2013; Monteux *et al.* 2016). Estimates of the final formation stages of the Earth (the core formation and the moon forming impact event) show that this did not extend beyond 140 Myr after the formation of the first solids (Rubie *et al.* 2007; Fischer and Nimmo 2018). Evidence from Hadean zircons show that oceans likely existed on Earth within ~ 150 -250 Myr of the start of Solar System formation (Mojzsis *et al.* 2001; Wilde *et al.* 2001). This indicates that water (and accompanying organics and other volatiles) must have arrived as Earth was forming, consistent with models for Earth’s chemical evolution during its accretion (Wood *et al.* 2010; Dauphas 2017).

This chapter reviews current paradigms for the origins of Earth’s water. As water delivery is inherently linked with planet formation, we summarize the geochemical, cosmochemical, astrochemical, astronomical, and dynamical evidence for how habitable worlds form, addressing in particular the origin of water on rocky planets. Isotopes and noble gases are powerful tracers of the early solar system chemical processes in the protoplanetary disk. Interpreting these fingerprints requires an understanding of how the planetesimals grew, moved around and were eventually incorporated into habitable planets (see Fig. 1). The remainder of section 1 introduces the history of exploring the origin of water through the isotopic record. Section 2 summarizes the dynamical and chemical constraints and processes for solar system formation, Section 3 summarizes models for the

delivery of water to the inner solar system and Section 4 discusses the implications.

1.2. D/H As a Tracer of Earth’s Water

Deuterated molecules have a highly temperature sensitive chemistry that can provide information about the physical conditions at the time of their formation. The original D/H ratio set in the big bang (*Spergel et al.* 2003) and altered by stellar nucleosynthesis is measured from interstellar absorption lines as starlight passes through diffuse gases. Deuterium is enriched in interstellar ices in cold dense regions in molecular clouds via complex gas phase and gas-grain chemistry reaction networks (*Millar et al.* 1989).

It had long been known that the D/H ratio of Earth’s oceans (e.g., Standard Mean Ocean Water, $D/H_{\text{SMOW}} = 15.576 \times 10^{-5}$, *Lécuyer et al.* 1998) was significantly elevated (by a factor of 6.4) above that of the expected protosolar value (*Geiss and Gloeckler* 1998, see Table 1). The measurement of a similarly elevated D/H value in water ($2 \times \text{SMOW}$) for Comet Halley by the *Giotto* mission (*Eberhardt et al.* 1987, 1995) led to the idea that comets could have been the source of Earth’s water (*Owen and Bar-Nun* 1995) and that D/H could serve as the “fingerprint” to identify the origin of inner solar system water.

However, as more measurements of D/H in comets were obtained (mostly of long period comets, LPCs; see Fig. 3) showing that the values were all elevated above that of SMOW (*Mumma and Charnley* 2011), it was clear that comets could not be the only source of Earth’s water.

Initially, D/H measurements from astronomical sources were compared to Earth’s oceans. However, since the oceans likely do not represent the bulk of Earth’s water inventory, the comparison should be made to Earth’s bulk D/H. The Earth’s oceans are not a closed system; they interact with the atmosphere, and water is mixed into the mantle via subduction. One scenario invoking large-scale loss of an early H-rich atmosphere proposes that the atmospheric

Astronomical and solar system D/H values			
Source	D/H Value		Note
	$[\times 10^{-5}]$	$\delta D [\text{‰}]^\dagger$	
Big Bang	2.62 ± 0.19	-832 ± 12	1
Local ISM gas	2.3 ± 0.24	-852 ± 15	2
ISM/YSO ice	10-100	$-350 \rightarrow +5419$	3
Protosolar	2.0 ± 0.35	-872 ± 22	4
SMOW	15.57	0	5
Earth Mantle	< 12.2	< -217	6
Giant planets	1.7-4.4	$-890 \rightarrow -717$	7
Mars Mantle	< 19.9	< 278	8
C-Chondrites	8.3-18	$-467 \rightarrow +156$	9
Rings, moons	14.3-130	$-82 \rightarrow +7346$	10
Comets	16-53	$+27 \rightarrow +2402$	11

Table 1: Notes: $^\dagger \delta D$ in per mil [‰] = $([D/H]_{\text{sample}} / [D/H]_{\text{SMOW}} - 1) \times 1000$. [1] *Spergel et al.* (2003) [2] *Lin-sky* (2007) [3] *Cazaux et al.* (2011); *Coutens et al.* (2014) [4] *Geiss and Gloeckler* (1998) [5] *Lécuyer et al.* (1998) [6] *Hallis et al.* (2015) [7] As measured in H_2 *Lellouch et al.* (2001); *Feuchtgruber et al.* (2013); *Pierel et al.* (2017) [8] *Hallis* (2017) [9] *Alexander et al.* (2012b) [10] *Waite et al.* (2009); *Clark et al.* (2019) [11] *Bockelée-Morvan et al.* (2015); *Altwegg et al.* (2015).

D/H may have increased over the age of the solar system by a factor of 2-9 \times (*Genda and Ikoma* 2008). Determining the Earth’s primordial D/H ratio thus requires sampling a primitive undegassed mantle source. Magma ocean crystallization models (*Elkins-Tanton* 2008) suggest that there may have been small volumes of late-solidifying material in the first 30-75 Myr of Earth’s history that still exist near the core mantle boundary. Mantle plumes in Hawai’i, Iceland, and Baffin Island appear to have tapped into undegassed, deep mantle sources, based on their He isotope ratios (*Starkey et al.* 2009; *Stuart et al.* 2003; *Jackson et al.*

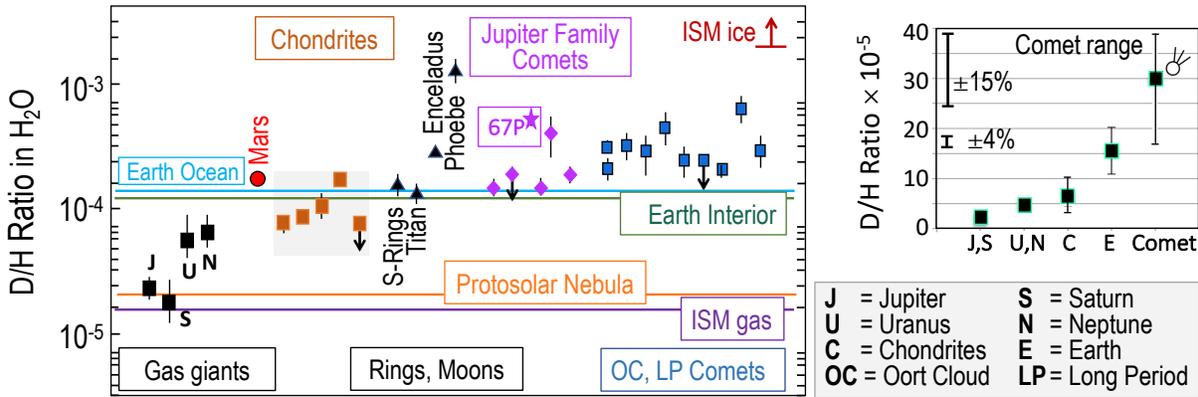


Fig. 3.— D/H measurements from a variety of solar system reservoirs. The values and references are shown in Table 1. While high precision measurements of D/H can discriminate between source reservoirs, some reservoirs have similar D/H values. D/H alone can not identify the source of inner solar system water.

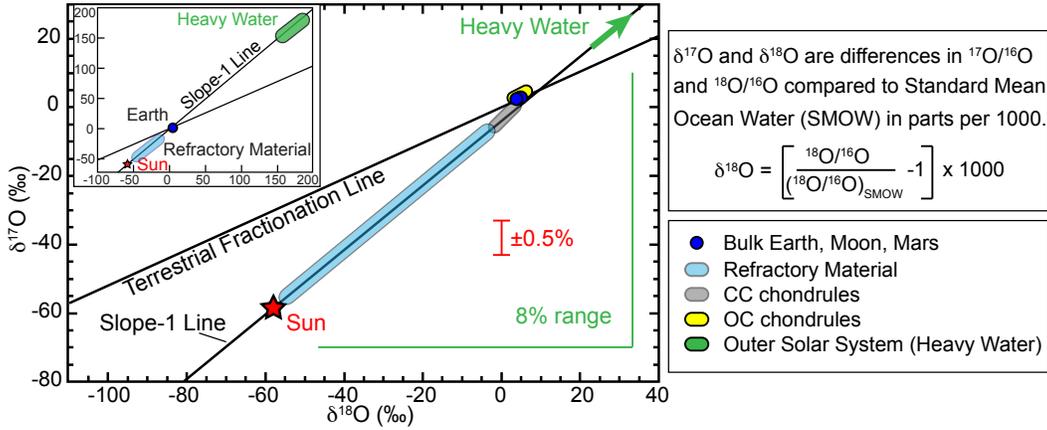


Fig. 4.— The range of oxygen isotopic variation in the solar system is small, so distinguishing reservoirs requires very high precision measurements.

2010). Measurements from the Icelandic plume show a measurement for Earth’s mantle that has a D/H lower than that of the oceans (Hallis *et al.* 2015, see Section 3.1.2), although this may not be representative of the whole mantle.

Among solar system water reservoirs, only carbonaceous chondrites have D/H ratios that span the estimates for Earth’s ocean and interior (Marty and Yokochi 2006; Marty 2012; Hallis *et al.* 2015; Alexander *et al.* 2012b). While chondritic water is isotopically lighter than Earth’s water, chondritic organics are heavier (Alexander *et al.* 2012a). These two reservoirs (water and organics) are expected to have equilibrated during accretion, and it is the bulk D/H isotopic composition that should be considered.

1.3. Oxygen Isotopic Variations

Isotopic measurements of D/H alone are insufficient to uniquely ascertain a formation location in the disk because of the complexity of disk chemical models (see § 1.6). Oxygen has three isotopes whose variation in the disk depends on different physical processes, thus the variation can be used as an independent tracer. The standard isotope notation is defined as:

$$\delta^{17}\text{O} = \left(\frac{^{17}\text{O}/^{16}\text{O}_{\text{sample}}}{^{17}\text{O}/^{16}\text{O}_{\text{SMOW}}} - 1 \right) \times 1000, \quad (1)$$

(similarly for $\delta^{18}\text{O}$).

The oxygen isotopic composition of the Sun inferred from samples of the solar wind returned by the Genesis spacecraft is ^{16}O -rich (McKeegan *et al.* 2011), whereas nearly all solar system solids are ^{16}O -depleted relative to the Sun’s value (see Fig. 4). Exceptions are refractory inclusions that formed from a gas of approximately solar composition and are ^{16}O -rich (Scott and Krot 2014). Most physical and chemical fractionation processes depend on mass, and on an oxygen three-isotope plot of $\delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ samples should fall on a line with a slope of ~ 0.52 . Most samples from Earth (excluding the atmosphere) fall along

this line, called the Terrestrial Fractionation line (TFL). However, the compositions of chondrules and refractory inclusions in the primitive (unmetamorphosed and unaltered) carbonaceous chondrites fall along a mass-independent fractionation line with a slope of ~ 1 (see Section 2.3.2). The physical processes controlling the distribution of oxygen isotopes in primitive solar system bodies are different from those for D/H, thus the oxygen isotopic composition of water can also provide clues about its origins (see Section 2.3.2).

1.4. Nitrogen Isotopic Variations

Nitrogen isotopes can provide additional constraints for planetesimal formation distances (Alexander *et al.* 2018a). There is a general trend of increasing $\delta^{15}\text{N}$ with increasing distance of formation from the Sun, although again, we only have these measurements for a small number of comets. While many carbonaceous chondrites have nitrogen isotopic ratios that match that of the Earth, cometary values are very different from the telluric value. The large cometary ^{15}N excess relative to Earth’s atmosphere indicates that their volatiles underwent isotopic fractionation at some point in the early solar system. Within the uncertainties on estimates of volatile budgets, Marty (2012) and Alexander *et al.* (2012b) have proposed that Earth’s inventory of H, C and noble gases may be matched with a few percent CM/CI chondritic material (see Fig. 5). However, Earth’s bulk nitrogen content appears to be depleted by an order of magnitude relative to those elements. It remains uncertain whether Earth preferentially lost much of its nitrogen during giant impacts or whether there remains an as-yet-unidentified reservoir of nitrogen in Earth’s interior.

1.5. Noble Gases

While Earth’s D/H may be a match for carbonaceous chondrites, the noble gases are not a match (Owen and Bar-Nun 1995, 2000) and an additional solar component is re-

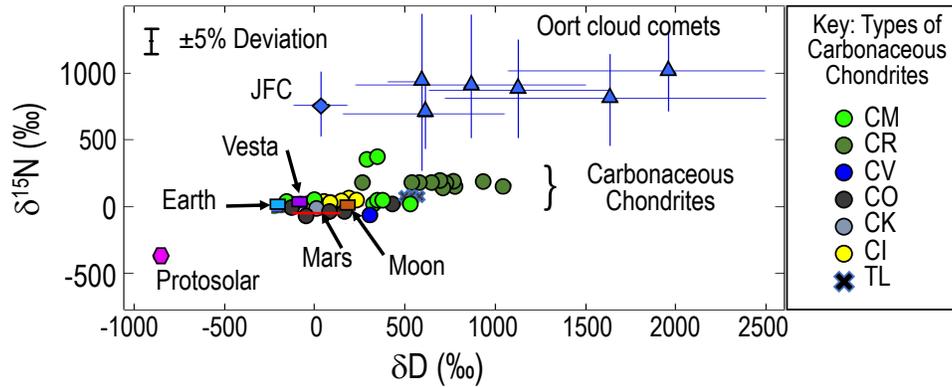


Fig. 5.— Combining nitrogen and hydrogen isotope ratios helps discriminate between reservoirs. The N-isotope difference between the group defined by Earth, Vesta, the Moon, Mars, chondrites, the Oort cloud comets, and the protosolar value is large. The difference between the CR chondrites and the other chondrites is 15%. The cometary values are measured in a variety of different molecules including water, HCN and NH_3 . It is challenging to infer the bulk isotopic compositions.

quired. Ideas for how this solar component was acquired include: that it was accreted directly from the nebula, was solar wind implanted into the surfaces of small objects accreted by the Earth, or was delivered by cometary ices (see also the discussion in the Chapter by Zahnle & Carlson). The noble gas fractionation patterns for the Martian and terrestrial atmospheres are similar, both depleted in Xe relative to the other noble gases compared to carbonaceous chondrites. The first detection of noble gases in comets was from the *Rosetta* mission and showed that Ar and Kr were solar (Rubin *et al.* 2018), but there were deficits in the heavy Xe isotopes (Marty *et al.* 2017). This suggests that there was at least a small contribution of cometary volatiles that delivered little of Earth’s water but a significant fraction of its (atmospheric) noble gases (Marty *et al.* 2016, 2017).

1.6. Multiple Fingerprints are Needed

Generally, volatiles that have been heated and re-equilibrated with inner solar system gas will have a low (protosolar) D/H value, and bodies formed in the distant solar system will be high. Most of the early comet D/H measurements were from long period comets (LPCs), which were thought to form closer to the sun than the Jupiter family comets (JFCs). Based on the expectation that the JFCs likely formed in the colder outer disk and the LPCs formed in the giant planet region closer to the sun (Meech and Svoren 2004), it was expected that the JFCs would have an even higher D/H ratio than the LPCs. However, the D/H measurement in the *EPOXI* mission target, JFC 103P/Hartley 2 matched that of Earth’s oceans leading to claims that the JFC comet reservoir could have delivered Earth’s water (Hartogh *et al.* 2011).

More recently, the high D/H measurements from the *Rosetta* mission target (also a JFC; see Fig. 3) have been interpreted to imply that comets did not bring Earth’s water (Altwegg *et al.* 2015). However, there are two key uncertainties. First, cometary isotopic ratios were only measured

in certain molecules and may not represent the bulk isotopic compositions (recall that, while carbonaceous chondrites match Earth’s bulk D/H, chondritic water is isotopically lighter whereas chondritic organics are isotopically heavier; Alexander *et al.* 2012a). Second, there may be a correlation between measured D/H values and the level of cometary activity, with more active comets having lower D/H (Lis *et al.* 2019). This effect is likely to be small, however, and models show that this should not be a factor if comets are observed at perihelion (Podolak *et al.* 2002).

Many of these D/H measurements have stimulated the development of new disk chemical models when data did not match predicted trends (Aikawa *et al.* 2002; Willacy and Woods 2009; Jacquet and Robert 2013; Yang *et al.* 2013). The real issue is that the predicted D/H variation along the mid-plane from chemical models of protosolar disks is complex, and D/H alone is not sufficient to determine a formation distance to compare to dynamical models. This was seen with the *Rosetta* D/H measurement (Altwegg *et al.* 2015), which was consistent with several disk chemical and dynamical models (see Fig. 6).

There is an additional complication. The D/H of water in ordinary and R chondrites is higher than in carbonaceous chondrites (Alexander *et al.* 2012b), possibly due to either higher presolar water abundances in the inner solar system, or due to oxidation of metal by water and subsequent isotopic fractionation as the generated H_2 is lost (Alexander 2019a,b).

Finally, because of the complex chemistry and dynamical mixing as the planets grew, the chemical fingerprints are “smeared”. Multiple reservoirs can also have the same fingerprint. Thus, to understand the origins of inner solar system volatiles, we need to measure multiple isotopes, comparing these to the dynamical models.

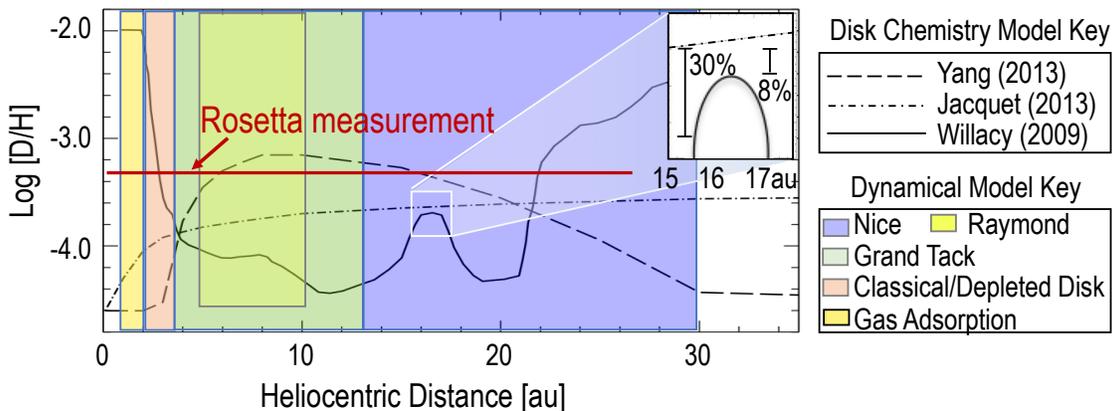


Fig. 6.— Measuring only D/H cannot uniquely determine an origin location. The *Rosetta* measurement from comet 67P/Churyumov-Gerasimenko is consistent with at least two disk chemical models predicting formation at several heliocentric distances—compatible with several dynamical models. Furthermore, disk chemical models can have similar D/H at different distances, and different dynamical models can scatter from overlapping regions.

2. Solar System Formation Constraints and Processes

Given that the origin of Earth’s water cannot be decoupled from its formation, we must consider the large-scale constraints on solar system formation. In this section, we briefly summarize the empirical constraints and the key processes of planet formation. For more detail we refer the reader to recent in-depth reviews focused on dynamical modeling and solar system formation (*Morbidelli and Raymond 2016; O’Brien et al. 2018*, also chapters by Zahnle & Carlson and by Raymond et al.).

2.1. Planet Formation Model Empirical Constraints

The following observations represent the fossil evidence of our solar system’s formation, which successful planet formation scenarios must reproduce (see *Chambers 2001; Raymond et al. 2009*).

2.1.1. The Planets’ Orbits

Most of the mass in terrestrial planets is concentrated in a narrow ring between the orbits of Venus and Earth. The terrestrial planets themselves have near-circular, coplanar orbits which for years posed a problem for models of terrestrial accretion. Meanwhile, the giant planets’ low-eccentricity but spread-out orbits may indicate an orbital instability in our solar system’s distant past (*Tsiganis et al. 2005*), albeit one that was far weaker than those inferred for exoplanet systems (*Raymond et al. 2010*).

2.1.2. Small Body Populations

Solar system small bodies are the leftovers of planet formation, although there is no reason to think that they are a representative sample. The asteroid belt is very low in mass but has an excited orbital distribution. In broad strokes, the inner belt is dominated by dry objects (such as the S-types) and the outer belt by hydrated asteroids (e.g., the C-types)

(*Gradie and Tedesco 1982; DeMeo and Carry 2013*). In addition to the asteroids, volatile-rich bodies include comets, small satellites, and Kuiper belt objects. The Kuiper belt contains a total of ~ 0.1 Earth masses, M_{\oplus} , (*Gladman et al. 2001*) and the Oort cloud up to a few M_{\oplus} (*Boe et al. 2019*, and references therein).

For a long time it was believed that comets formed in distinct regions, e.g., that the LPCs formed in the giant planet region and were scattered to the Oort cloud during formation, and that the JFCs were formed further out in the region of the Kuiper belt—eventually getting perturbed inward, during which time they became Centaurs, until their orbits were influenced by Jupiter (*Meech and Svoren 2004*). However, while there are clear trends in comet chemistry (*A’Hearn et al. 1995; Mumma and Charnley 2011*), they have not been clearly tied to dynamical class. Comets likely formed over a range of distances outside the solar system’s snow line and have experienced significant dynamical scattering. In considering possible sources for Earth’s water we must therefore consider these objects as a population because individual comets cannot be traced back in time; rather, they sample the entire disk outside the snow line.

2.1.3. Meteorite Constraints on Growth Timescales

Isotopic analyses of different types of meteorites provide vital constraints on formation timescales of different types of objects. CAIs, the oldest dated solids to have formed in the solar system, are generally used as “time zero” for planet formation. Age estimates of iron meteorites provide upper limits to the formation timescales of differentiated bodies (*Kruijer et al. 2014*). The existence of two types of chondritic meteorites with different isotopic anomalies (non-carbonaceous and carbonaceous) but similar ages has been interpreted as evidence for the rapid growth of Jupiter’s core, which would have provided a bar-

rier between these populations (*Kruijer et al.* 2017; *De-sch et al.* 2018a, see also chapter by Zahnle & Carlson). Finally, the Hf/W system provides estimates of the timing of core formation, and suggest that Mars’ growth was rapid (*Nimmo and Kleine* 2007; *Dauphas and Pourmand* 2011), whereas Earth’s was prolonged (*Kleine et al.* 2009; *Jacobson et al.* 2014).

These constraints are inherently tied to the conditions of planet formation. For example, numerical experiments have shown that a smooth disk of solids extending from Mercury’s orbit out to Jupiter’s generally fails to reproduce the solar system because (1) the terrestrial planets’ orbits are overly excited (*Chambers* 2001; *O’Brien et al.* 2006; *Raymond et al.* 2006b); (2) Mars is too massive and grows too slowly (*Raymond et al.* 2009; *Fischer et al.* 2014; *Izidoro et al.* 2015b); and (3) the asteroids’ orbits are under-excited (*Izidoro et al.* 2015b). Although we note that these problems may be solved if the giant planet instability happens *during* terrestrial planet formation; (*Clement et al.* 2018, see Section 3 and Figure 11 for a comparison between models).

2.2. Key Planet Formation Processes

Planet formation models are built of processes. Each process can be thought of as a puzzle piece, which must be assembled into a global picture of planetary growth (see the chapter by Raymond et al. for a review dedicated entirely to this endeavor for the solar system and exoplanet systems). We now very briefly summarize the key planet formation processes from the ground up.

2.2.1. Disk Structure and Evolution

The underlying structure and dynamics of protoplanetary disks remain poorly understood (*Morbidelli and Raymond* 2016). An essential piece of the story is how angular momentum is transported within disks (*Turner et al.* 2014). The radial surface density of gas and dust sets the stage for planet formation. Within a disk, the gas is subject to hydrodynamic pressure forces as well as gravity, and its motion deviates from pure Keplerian motion, with radial velocities that are generally slightly slower than the Keplerian velocity. Dust grows and drifts within the disk (*Birnstiel et al.* 2012). Dust accumulates at pressure bumps, narrow rings at which the gas velocity matches the Keplerian velocity such that the drag force disappears (*Haghighipour and Boss* 2003). Exterior to a pressure bump the gas velocity is sub-Keplerian such that dust particles feel a headwind, lose orbital energy and drift radially inward. Just interior to pressure bumps the gas velocity is super-Keplerian so particles feel a tailwind, driving them back outward. Very small dust particles remain strongly coupled to the gas, and large bodies have enough inertia to drift slowly; the fastest-drifting particles are “pebbles” (e.g., *Ormel and Klahr* 2010; *Lambrechts and Johansen* 2012). As disks evolve they cool down, and locations associated with specific temperatures – e.g., the *snow line*, the radial distance beyond which a

volatile (such as water) may condense as ice – move inward. Gaseous disks are observed to dissipate on a characteristic timescale of a few Myr (*Haisch et al.* 2001; *Hillenbrand et al.* 2008).

2.2.2. Planetesimal Formation

Planetesimals are the smallest macroscopic bodies for which gravity dominates over hydrodynamical forces. Their origin has long been difficult to reproduce with formation models because any growth model must traverse the size scale at which particles start to decouple from the gas motion. These intermediate-sized particles then experience the headwind that causes them to rapidly spiral inward, preventing aggregation into larger bodies. This occurs at cm- to m-sizes, so this is sometimes called the “meter barrier” (*Weidenschilling* 1977). New models have demonstrated that mm-sized particles can be concentrated and clump directly into planetesimals via processes such as the streaming instability (*Youdin and Goodman* 2005; *Johansen et al.* 2009; *Simon et al.* 2016; *Yang et al.* 2017), thus jumping over the meter barrier. The conditions for triggering the streaming instability vary in time and position within a given disk (*Drążkowska and Alibert* 2017; *Carrera et al.* 2017).

2.2.3. Pebble Accretion

Once planetesimals form, they may grow by accreting other planetesimals as well as pebbles drifting inward through the disk (*Johansen and Lambrechts* 2017). Here, “pebbles” are taken to be particles that drift rapidly through the gas and are typically mm- to cm-sized for typical disk parameters (*Ormel and Klahr* 2010; *Lambrechts and Johansen* 2012). Pebble accretion can be extremely fast under some conditions and objects can quickly grow to many Earth-masses in the giant planet region if there is a sufficient reservoir of pebbles (*Lambrechts and Johansen* 2014; *Morbidelli et al.* 2015). Pebble accretion is self-limiting, as above a given mass (typically 10 – 20 M_{\oplus} at Jupiter’s orbit *Bitsch et al.* 2018) a core generates a pressure bump exterior to its orbit that holds back the inward-drifting pebbles.

2.2.4. Gas Accretion

Cores that grow large enough and fast enough accrete gas from the disk. The *core-accretion* scenario for giant planet formation (*Pollack et al.* 1996) envisions the growth of $\sim 10 M_{\oplus}$ cores followed by a slow phase of gas accretion. When the mass in the gaseous envelope is comparable to the core mass, gas accretion can accelerate and quickly form Saturn- to Jupiter-mass gas giants. During this rapid accretion phase, the orbits of nearby planetesimals are destabilized and many are scattered inward, contaminating the inner planetary system (*Raymond and Izidoro* 2017b). Given that most cores are not expected to grow into gas giants, this model predicts a much higher abundance of ice giant-mass planets relative to gas giants, which has been confirmed by exoplanet statistics (*Gould et al.* 2010; *Mayor*

et al. 2011; *Petigura et al.* 2013). On the other hand, some giant exoplanets – in particular those at large orbital radii – may form rapidly by direct gravitational collapse (*Boss* 1997; *Mayer et al.* 2002; *Boley* 2009).

2.2.5. Orbital Migration

Gravitational interactions between a growing planet and its nascent gaseous disk generate density perturbations which torque the planet’s orbit and cause it to shrink or grow (i.e., to *migrate* inward or outward, *Kley and Nelson* 2012; *Baruteau et al.* 2014). Migration matters for planets more massive than $\sim 0.1 - 1 M_{\oplus}$. In most cases migration is directed inward but the corotation torque, which depends on the local disk conditions, can in some instances be positive and strong enough to drive outward migration (*Kley and Crida* 2008; *Paardekooper et al.* 2011). In the context of the entire disk, in some regions planets migrate towards a common location, although these convergence zones themselves shift as disks evolve (*Lyra et al.* 2010; *Bitsch et al.* 2015). Above a critical mass, a planet clears an annular gap in the gaseous disk and migration transitions to “type 2” (as opposed to “type 1” for planets which do not open gaps *Lin and Papaloizou* 1986; *Ward* 1997; *Crida et al.* 2006). Type 2 migration is generally slower than type 1 migration and is again directed inward in most instances.

2.2.6. Giant Impacts

Impacts between similar-sized massive objects are thought to be common in planet formation. The late phases of terrestrial planet growth are attributed to a small number of ever-larger giant impacts between growing rocky bodies (*Wetherill* 1991; *Agnor et al.* 1999). Giant impacts among large ice-rich cores have been invoked to explain the large obliquities of Uranus and Neptune (*Benz et al.* 1989; *Izidoro et al.* 2015a). The final giant impact on Earth is believed to be the one that led to the formation of the Moon (*Benz et al.* 1986; *Canup and Asphaug* 2001).

2.2.7. Late Accretion

Giant impacts are thought to be energetic enough to trigger core formation events, which sequester siderophile (“iron-loving”) elements in the planet’s core (*Harper and Jacobsen* 1996). Highly-siderophile elements (HSEs) in a planet’s mantle and crust are, therefore, considered to have been delivered by impacts with planetesimals *after* the giant impact phase (*Kimura et al.* 1974; *Day et al.* 2007; *Walker* 2009). This is called late accretion or the late veneer. Earth’s HSE budget implies that roughly 0.5% of an Earth mass was delivered in late accretion (*Walker et al.* 2015; *Morbidelli and Wood* 2015).

2.2.8. Dynamical Instability

After the disappearance of the gaseous disk, systems of planets may become unstable. This applies both to systems of low-mass planets (i.e., super-Earths) and gas giants (*Raymond et al.* 2018b). Our solar system’s giant plan-

ets are thought to have undergone such an instability (*Tsiganis et al.* 2005; *Morbidelli et al.* 2007; *Levison et al.* 2011). This instability can explain the giant planets’ orbits and a multitude of characteristics of small body populations (for a review, see *Nesvorný et al.* 2018a). This “Nice model” was originally conceived to explain the Late Heavy Bombardment (*Gomes et al.* 2005), a perceived spike in the impact rate on the Moon starting roughly 500 Myr after planet formation (*Tera et al.* 1974). However, a new interpretation of the evidence has led to the conclusion that there was probably no delayed bombardment but rather a smooth decline in the impact rate in the inner solar system (*Boehnke and Harrison* 2016; *Zellner* 2017; *Morbidelli et al.* 2018; *Hartmann* 2019). The instability is still thought to have occurred but may have taken place anytime in the first ~ 100 Myr of solar system history (*Nesvorný et al.* 2018b). The broad eccentricity distribution of exoplanets implies that instabilities are common (*Chatterjee et al.* 2008; *Ford and Rasio* 2008; *Jurić and Tremaine* 2008, the median eccentricity of giant exoplanets is ~ 0.25). Instabilities in most giant planet systems are likely to have been far more violent than in our own solar system (*Raymond et al.* 2010; *Ida et al.* 2013), and to have often disrupted growing terrestrial exoplanets and outer planetesimal disks (*Veras and Armitage* 2006; *Raymond et al.* 2011, 2012).

2.3. Protoplanetary Disk Chemistry

Disk chemistry is responsible for the key chemical markers that can be used to trace the transport of water in the disk and this is transferred to the planetesimals as ice freezes on dust grains. The isotopic composition is imprinted on planetesimals when they form. However, given the widespread planetesimal scattering and dynamical re-arrangement during and after planetary formation (e.g., *Levison et al.* 2008; *Walsh et al.* 2011a; *Raymond and Izidoro* 2017a), it is important to recognize that the present-day orbits of Solar System bodies may not reflect their formation locations. For example, while Jupiter is often used as the boundary between the inner and outer Solar System, recent models suggest that the parent bodies of the carbonaceous chondrites likely originated beyond Jupiter (*Walsh et al.* 2011a; *Kruijer et al.* 2017; *Raymond and Izidoro* 2017a).

Unique chemical signatures are thus imprinted on the icy material that is incorporated in the planetesimals that grow to form planets. Planet formation models incorporate volatile condensation onto grains (*Grossman* 1972) and water transport and condensation beyond the snow line (*Stevenson and Lunine* 1988; *Garaud and Lin* 2007), inside which the temperatures are too warm for water ice to remain stable.

Modern protoplanetary disk evolution models are based on chemical networks developed for the interstellar medium (ISM), and include disk structure, isotopic fractionation, and gas transport and incorporate the physics of grain growth, settling and radial migration. Although models are always incomplete and remain crude representations of

reality, recent observations have provided key constraints to help refine the models. Models and observations (*Pontoppidan et al.* 2014; *van Dishoeck et al.* 2014) reveal radial and vertical variations in thermal and chemical disk structure (Fig. 1). Infrared observations from *Spitzer* and *Herschel* (*Zhang et al.* 2013; *Du and Bergin* 2014) and new spatially-resolved Atacama Large Millimeter Array (ALMA) telescope observations constrain the models (*Qi et al.* 2013). ALMA observations also set limits on ionization in protoplanetary disks (*Cleeves et al.* 2014a, 2015), providing constraints on models of deuterium-enrichment in water (*Cleeves et al.* 2014b) due to ion-molecule reactions. These state-of-the-art disk-chemistry models (*Willacy and Woods* 2009; *Jacquet and Robert* 2013; *Yang et al.* 2013) make very different testable predictions of radial isotope distributions in protoplanetary disks.

2.3.1. Deuterium Chemistry

Observations and detailed models provide a good understanding of the complex chemistry of cold interstellar clouds in which new stars form (*Bergin and Tafalla* 2007b). For example, low-temperature ion-molecule reactions drive deuterium fractionation (*Millar et al.* 1989). Water ice becomes enriched in deuterium, with a D/H ratio of 0.001 to 0.02 compared to a cosmic abundance of 2.6×10^{-5} . Physical processes in the disk control the temperature and radiation-field dependent chemistry. In the hot inner region of the disk, isotopic exchange reactions between water vapor and hydrogen gas reduce the D/H ratio to $\sim 2 \times 10^{-5}$, the “protosolar” value (see Table 1). In the nebula’s outer disk, D/H evolved from an initial supply of water from molecular cloud (“ISM ice” in Fig. 3) that was highly enriched in deuterium via ion-molecule and gas-grain reactions (*Herbst* 2003; *van Dishoeck et al.* 2013) at temperatures < 30 K. Indeed, high D/H water probably cannot be produced within disks themselves and must be inherited (*Cleeves et al.* 2014a, 2016). Sharp gradients in the disk’s D/H isotopic composition arise from mixing between inherited water and water that had re-equilibrated by isotopic exchange with hydrogen in the hot inner disk (sometimes called the *protosolar nebula*, *Geiss and Gloeckler* 1998; *Lellouch et al.* 2001; *Yang et al.* 2013; *Jacquet and Robert* 2013). The radial extent of equilibration is uncertain, as stellar outbursts (also called FU Orionis outbursts) can strongly heat the disk for short periods (years to decades) and drive the snow line out to tens of au (*Cieza et al.* 2016).

2.3.2. Oxygen Isotope Fractionation

The most widely accepted mechanism for explaining the oxygen isotopic diversity among solar system materials is CO self-shielding (*Lyons and Young* 2005). The three oxygen isotopes (^{16}O , ^{17}O , ^{18}O) have dramatically different abundances (~ 2500 , 1, 5, respectively). The wavelengths necessary to dissociate $^{12}\text{C}^{16}\text{O}$, $^{12}\text{C}^{17}\text{O}$, and $^{12}\text{C}^{18}\text{O}$ are distinct, and the number of photons at each wavelength is

similar in the UV continuum. At the edge of a dense molecular cloud or accretion disk, UV light dissociates the same fraction of all the three isotopologues. But as the light penetrates into the cloud or disk, the photons that dissociate the $^{12}\text{C}^{16}\text{O}$ are depleted by absorption, so deeper in the cloud only $^{12}\text{C}^{17}\text{O}$ and $^{12}\text{C}^{18}\text{O}$ are dissociated. The resulting oxygen ions can either recombine into CO or combine with H_2 to form H_2O . Deeper in the cloud, the H_2O will be enriched in ^{17}O and ^{18}O . If the solar system started out with the composition of the Sun, self-shielding would have produced isotopically heavy water in the outer parts of the disk. *Yurimoto and Kuramoto* (2004) also suggest that this self-shielding could occur in the pre-solar molecular cloud, and this material was transported into the solar nebula by icy dust grains during the cloud collapse. As they drifted in toward the sun and sublimated this enriched the inner disk gas.

An alternative mechanism to explain the oxygen isotopic diversity is the Galactic Chemical Evolution (GCE) model (*Krot et al.* 2010), although there are reasons why this model may not work (*Alexander et al.* 2017). According to the GCE model, the solids and gas in the protosolar molecular cloud had different ages and average compositions; the solids were younger and ^{16}O -depleted relative to the gas. According to the CO self-shielding model, O-isotope compositions of the primordial and thermally processed solids must follow a slope 1.0 line, whereas there is no a-priori reason to believe that the GCE model results in the formation of solid and gaseous reservoirs falling on a slope 1.0 line (*Lugaro et al.* 2012). Patterns of oxygen isotope fractionation can be compared against these two models.

Models combined with *Genesis* observations (*McKeegan et al.* 2011) indicate that primordial dust and gas had the same ^{16}O -rich composition as the Sun. The result is an array of points with a slope ~ 1 on an oxygen three-isotope plot (Fig. 4), with the initial CO plotted at the lower left (marked “Sun” on the diagram) and the $^{17,18}\text{O}$ -rich water plotted at the upper right (marked “Heavy Water”) (*Clayton et al.* 1973; *Yurimoto et al.* 2008). Outside the snow line, the heavy water froze on the surface of dust and settled to the disk mid-plane. Other compositions in the diagram can be produced by combining isotopically “heavy” water with isotopically “light” condensates with compositions similar to the Sun (*Lyons and Young* 2005; *Yurimoto and Kuramoto* 2004). The total range in oxygen isotope variation seen in the solar system is small (see range marked in Fig. 4), so distinguishing different reservoirs and formation distances requires high precision oxygen isotope information. Self-shielding depends on UV intensity and gas densities, and therefore relates to solar distance, and time.

2.3.3. Nitrogen Chemistry

Nitrogen fractionation in the disk is dominated by different physical mechanisms than for D/H and oxygen, thus providing a third independent tracer. The primordial neb-

ula and the Sun are significantly ^{15}N -depleted relative to Earth's atmosphere (Owen *et al.* 2001; Meibom *et al.* 2007; Marty *et al.* 2010; Anders and Grevesse 1989). Other reservoirs (CN and HCN in comets, some carbonaceous chondrite organics and Titan) are ^{15}N -enriched (Fig. 5). This large fractionation may be inherited from the protosolar molecular cloud, where it is attributed to low-temperature (<10 K) ion-molecule reactions (Anders and Grevesse 1989) or it could have resulted from photochemical self-shielding effects in the protoplanetary disk (Heays *et al.* 2014; Lyons 2012); the radial dependence on isotopic composition will differ significantly between these mechanisms. We expect the radial dependence of nitrogen-isotopes will be similar to those of oxygen. However, the radial dependence is additionally subject to low-temperature effects, active in the outer disk that is exposed to X-rays, making it distinguishable from oxygen.

2.3.4. Noble Gases as a Thermometer

When water ice condenses from a gas at temperatures less than 100K, it condenses in the amorphous form and can trap other volatiles. The amount of the trapped volatiles and their isotopic fractionation is a sensitive function of trapping temperature and pressure (Bar-Nun *et al.* 1985; Yokochi *et al.* 2012; Rubin *et al.* 2018). Over the age of the solar system, solar insolation and impacts can heat many small bodies above 137K, the amorphous ice crystallization temperature. When the ice crystallizes, a fraction of the trapped gases is retained in the water ice (possibly in the form of clathrates Rubin *et al.* 2018; Laufer *et al.* 2017) and is released only when the ice sublimates. This is seen consistently in laboratory experiments (Bar-Nun *et al.* 1988). Measurements of the $^{84}\text{Kr}/^{36}\text{Ar}$ ratio can provide a sensitive indication of temperature at which the gases were trapped (Mousis *et al.* 2018), and this can be linked through disk chemistry models to location in the protoplanetary disk.

3. Models for the Origin of Earth's Water and Their Context in Planet Formation

We now delve into the depths of models that describe exactly how Earth may have acquired its water. There are two categories of models: those that propose that Earth's water could have been sourced locally, and those that require the *delivery* of water from more distant regions.

Below we explain how each model works and its inherent assumptions. For some models that requires going into the dynamics they invoke to sculpt the solar system. We then confront each model with the empirical constraints laid out in Section 2.1.

3.1. Local accretion

To date, two models have been proposed that advocate for a local source of water on the terrestrial planets. Here we describe those models and their challenges.

3.1.1. Adsorption Onto Grains

It has been suggested that water could be “in-gassed” into growing planets (e.g., Sharp 2017). Drake (2004) and Muralidharan *et al.* (2008a) proposed that water vapor could be adsorbed onto silicate grains. This would allow for a *local* source of water at 1 au within the Sun's planet forming disk. Density functional theory calculations have shown that water vapor can indeed be adsorbed onto forsterite (Muralidharan *et al.* 2008b) or olivine (Stimpff *et al.* 2006; Asaduzzaman *et al.* 2014) grains. In principle, this mechanism can explain the accretion of multiple oceans of water onto Earth.

There are four apparent issues with this model. First, it cannot account for the delivery of other volatiles to Earth including carbon, nitrogen and the noble gases. In fact, this model would require an additional, H-depleted source for these species. Second, while the mechanism may accrete a water budget of perhaps a few oceans, it does not account for collisional loss of water as planetesimals grow, which can be substantial (Genda and Abe 2005). Second, it begs the question of why the enstatite chondrite meteorites – which offer a close match to Earth's composition (albeit with some important differences, such that Earth cannot be made entirely of enstatite chondrites; e.g., Dauphas 2017) – failed to incorporate any water and are extremely dry. Third, this mechanism implies that Earth's water should have the same isotopic signature as the nebular gas. However, the D/H ratio of the disk gas is likely to have been the same as the Sun's, which is a factor of $6.4\times$ lower than Earth's oceans (see Geiss and Gloeckler 1998, and Section 1). Finally, disk evolution models find that an individual parcel of gas in the vicinity of the snow line moves radially much faster than the snow line does (Morbidelli *et al.* 2016). This means that the water vapor in the inner disk likely does not remain but rather moves inward and is accreted onto the star much more quickly than it can be replenished. The inner disk's gas is therefore dry for a large fraction of the disk lifetime.

3.1.2. Oxidation of a Primordial H-rich Atmosphere

Ikoma and Genda (2006) also proposed that Earth's water could have been acquired locally, but as a result of reactions between Earth's primordial atmosphere and surface. During the magma ocean phase, atmospheric hydrogen can be oxidized by gas-rock interactions and produce water. A magma ocean phase that meets the criteria for this mechanism is expected for planets more massive than $\sim 0.3 M_{\oplus}$ (Ikoma and Genda 2006), although the duration of a magma ocean is also a strong function of orbital distance (Hamano *et al.* 2013).

This mechanism produces terrestrial water directly from nebular gas. Yet the D/H ratio of nebular gas is a factor of $\sim 6.4\times$ lower than Earth's (Geiss and Gloeckler 1998). However, most of this early hydrogen-rich atmosphere had to escape (Jean's escape), and the escape process leads to fractionation and an increase in the D/H ratio. Genda and

Ikoma (2008) showed that the D/H of Earth’s water can increase to its present-day value for certain values of the efficiency and timescale of hydrogen escape. However, the collateral effects of this loss on the isotopic fractionation of other species such as the noble gases remains unaddressed. Given that nitrogen should not be fractionated by this process, it appears to imply that Earth should have a Solar nitrogen isotopic composition, which is not the case (*Marty* 2012).

Measurements of water thought to be sourced from an isolated deep mantle reservoir yield D/H values closer to the nebular one (*Hallis et al.* 2015). This indicates that at least a fraction of Earth’s water may have a nebular origin. There is also circumstantial evidence from noble gases to support the idea that Earth had a primordial nebular atmosphere (*Dauphas* 2003; *Williams and Mukhopadhyay* 2019).

It remains to be seen whether nebular gas can explain the origin of the bulk of Earth’s water. This mechanism clearly requires Earth to have accreted and later lost a thick hydrogen envelope. While such a process is a likely outcome of growth within the gaseous disk: and there is evidence that many \sim Earth-sized exoplanets have thick Hydrogen atmospheres (e.g. *Wolfgang et al.* 2016), it seems a cosmic coincidence for the parameters to have been right for Earth to end up with the same D/H ratio (and $^{15}\text{N}/^{14}\text{N}$ ratio) as carbonaceous chondrites (*Marty* 2012). Carbonaceous chondrite-like objects thus seem a more likely source for Earth’s water.

3.2. Water Delivery

An alternate explanation for the origin of Earth’s water is delivery from the outer Solar System. The following models invoke sources of water that are separated from Earth’s orbit. Hence water is “delivered” from these regions to the Earth. These models are driven by a number of processes, including a combination of the moving snow line and drifting pebbles (Section 3.2.1), widening of terrestrial planets’ feeding zones (Section 3.2.2), gravitational scattering of planetesimals during the growth and migration of the giant planets (Section 3.2.3), and inward migration of large planetary embryos (Section 3.2.4).

3.2.1. Pebble “Snow”

As disks evolve and thin out, they cool down. Condensation fronts move inward (*Dodson-Robinson and Bodenheimer* 2010), including the water-ice snow line, located at $T \sim 150$ K. The exact evolution of the snow line depends on the thermal evolution of the disk and therefore on the assumed heating mechanisms, the most important of which are stellar irradiation and viscous heating. For alpha-viscosity disk models, the snow line starts in the Jupiter-Saturn region and moves inside 1 au within 1 Myr or so (*Sasselov and Lecar* 2000; *Lecar et al.* 2006; *Kennedy and Kenyon* 2008). The snow line also moves inward and generally ends up inside 1 au in more complex disk mod-

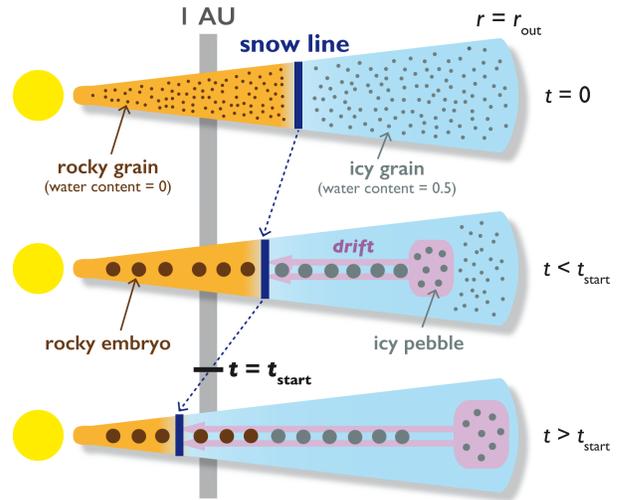


Fig. 7.— Snapshots in time of the evolution of a disk, showing how the snow line sweeps inward as the disk cools. Water may thus be delivered to rocky planets at 1 au by pebbles as they drift inward. We refer to this mechanism in the text as *pebble snow*. The pink region represents the “pebble production front”, the outward-moving radial location in the disk where pebbles grow from dust and start to drift inward. From *Sato et al.* (2016).

els (*Oka et al.* 2011; *Martin and Livio* 2012; *Bitsch et al.* 2015, 2019). However, it is worth noting that radial variations in viscosity may under certain assumptions keep the snow line outside 1 au for the disk lifetime (*Kalyaan and Desch* 2019). Figure 7 shows how a planet forming in a close-in, rocky part of the disk can become hydrated as the snow line sweeps inward (*Sato et al.* 2016).

Planetesimals are thought to form from dust and pebbles that are locally concentrated by drifting within the gas disk, followed by a phase of further concentration (e.g., by the streaming instability) to produce gravitationally bound objects (see, e.g., the review by *Johansen et al.* 2014). When planetesimals form, their compositions “lock in” the local conditions at that time. Yet most of the mass in solid bodies remains in dust and pebbles, which are small enough that their compositions likely change as they drift inward, in particular by losing their volatiles. Planetesimals continue to grow, in part by accreting pebbles (see Fig. 8 for a cartoon representation of the different phases of growth). The planetesimal and pebble phases overlap for the entire gas disk lifetime.

The evolution of the pebble flux controls the water distribution within the solids in the disk. When the snow line sweeps inward, the source of water is not condensing gas but inward-drifting particles (i.e., pebbles *Morbidelli et al.* 2016). This is because the gas’s radial motion is faster than the speed at which the snow line moves. As the snow line moves inward, it does not sweep over water vapor that can condense. Rather, the gas interior to the snow line is dry

(or mostly dry) simply because it moves more quickly than the snow line itself. The source of water at the snow line is instead in the form of ice-rich pebbles that drift inward from farther out in the disk.

There are two ways in which the flux of pebbles drifting inward through the disk can drop significantly: the pebble supply can be exhausted or the pebble flow can be blocked.

Dust within the disk coagulates to sizes large enough to drift inward rapidly (e.g., *Birnstiel et al.* 2012, 2016). However, dust grows into pebbles faster closer-in to the star, where accretion timescales are short and densities high. So the dust is consumed faster in the disk interior, resulting in an outward-moving front at which pebbles are produced, after which the pebbles drift inward (*Lambrechts and Johansen* 2014; *Ida et al.* 2016). When this *pebble production front* reaches the outer edge of the disk, the pebble flux drops drastically, as the source of pebbles is exhausted. Taking this into account limits the degree to which an inward-sweeping snow line can hydrate rocky planets because the mass in water-bearing pebbles drops off drastically in time. Nonetheless, in many cases this mechanism can deliver Earth-like water budgets (*Ida et al.* 2019).

The pebble flux can also be blocked, either by growing planets or by structures within the disk itself. Drifting particles follow the local pressure gradient (*Haghighipour and Boss* 2003), which drives pebbles monotonically inward in a perfectly smooth disk. However, pressure “bumps” act as traps for inward-drifting particles. These are radially-confined regions in which the gas pressure gradient becomes high enough that the gas orbits at the Keplerian speed, thus eliminating the headwind and associated drag forces on pebbles. Such traps may exist naturally within the disk, or they can be produced by growing planets. Once a planet reaches a critical mass (of roughly $20 M_{\oplus}$ at Jupiter’s orbit for typical disk parameters *Lambrechts and Johansen* 2014) it generates a pressure bump exterior to its orbit, which acts as a trap for inward-drifting pebbles (*Morbidelli and Nesvorný* 2012; *Lambrechts and Johansen* 2014; *Bitsch et al.* 2018). This not only starves the planet itself but also all other planets interior to its orbit.

When the pebble flux is blocked by a growing planet, it renders the concept of the snow line ambiguous. Given that inward-drifting pebbles are the source of water, the location at which the temperature drops below 150 K continues to move inward in the disk but does not bring any water along with it (recall that the gas is dry because it moves much faster than the snow line). In this way, the water distribution within a disk is “fossilized” at the time when an outer planet first grew large enough to block the pebble flux (*Morbidelli et al.* 2016). This fossilization is analogous to the snow line on a mountain, which marks the location at which the temperature reached zero Celsius while it was snowing (i.e., while pebbles were drifting). Once it stops snowing, the snow line on a mountain is no longer linked with the local temperature (as long as it does not warm up past the freezing point). After the inward drift of pebbles is cut off, redistribution of water within the disk requires dy-

namical processes that transport objects at larger size scales (e.g., via migration or gravitational scattering as invoked by the other water delivery mechanisms).

Can the pebble snow mechanism explain the origin of Earth’s water? The *pebble snow* mechanism can produce planets with water contents similar to Earth’s (*Ida et al.* 2019). However, understanding whether Earth could have accreted a large enough contribution from inward-drifting pebbles requires an understanding of the chemical properties of Earth’s building blocks.

Nucleosynthetic isotope differences are seen in a number of elements between the two main classes of meteorites: carbonaceous and non-carbonaceous (*Warren* 2011; *Kruijer et al.* 2017). These two populations appear to have been sourced from different reservoirs within the planet-forming disk, whose origins remain debated (*Nanne et al.* 2019). The rapid growth of Jupiter’s core has been invoked as a mechanism to keep the two populations separate, by preventing the drift of outer, carbonaceous pebbles into the inner solar system, which is thought to have been dominated by non-carbonaceous material (*Budde et al.* 2016; *Kruijer et al.* 2017).

Earth’s water’s D/H ratio is well-matched by carbonaceous chondrite meteorites (see Section 1.2 and Fig. 3). The pebble snow model would thus invoke carbonaceous pebbles as the source of Earth’s water, delivered late enough that the disk had cooled to the point that the snow line was located inside Earth’s orbit.

However, the pebble snow model does not appear to match empirical constraints. The latest-forming chondrites have ages that extend to roughly 4 Myr after CAIs (*Sugiura and Fujiya* 2014; *Alexander et al.* 2018a; *Desch et al.* 2018b), likely the full length of the disk lifetime. This seems to indicate that the two reservoirs remained spatially separated throughout. In other words, there are no known classes of chondritic meteorites with nucleosynthetic anomalies that lie in between, which would be a signature of the mixing.

This early separation between carbonaceous and non-carbonaceous pebble reservoirs seems to preclude drifting pebbles as the source of Earth’s water. If water-rich carbonaceous pebbles drifted inward to deliver water to Earth, then it should follow that the two reservoirs should have mixed and some meteorites should exist with intermediate compositions, which is not the case.

Dynamical models naturally implant carbonaceous planetesimals from Jupiter’s orbit and beyond into the asteroid belt and terrestrial planet region (discussed in detail in Section 3.2.3; *Walsh et al.* 2011a; *Raymond and Izidoro* 2017a). This may indicate that the non-carbonaceous S-type asteroids formed in the inner solar system whereas the carbonaceous C-types were implanted as planetesimals.

3.2.2. Wide Feeding Zones

In the well-studied framework of the *classical* model of terrestrial planet formation, the late phases of terres-

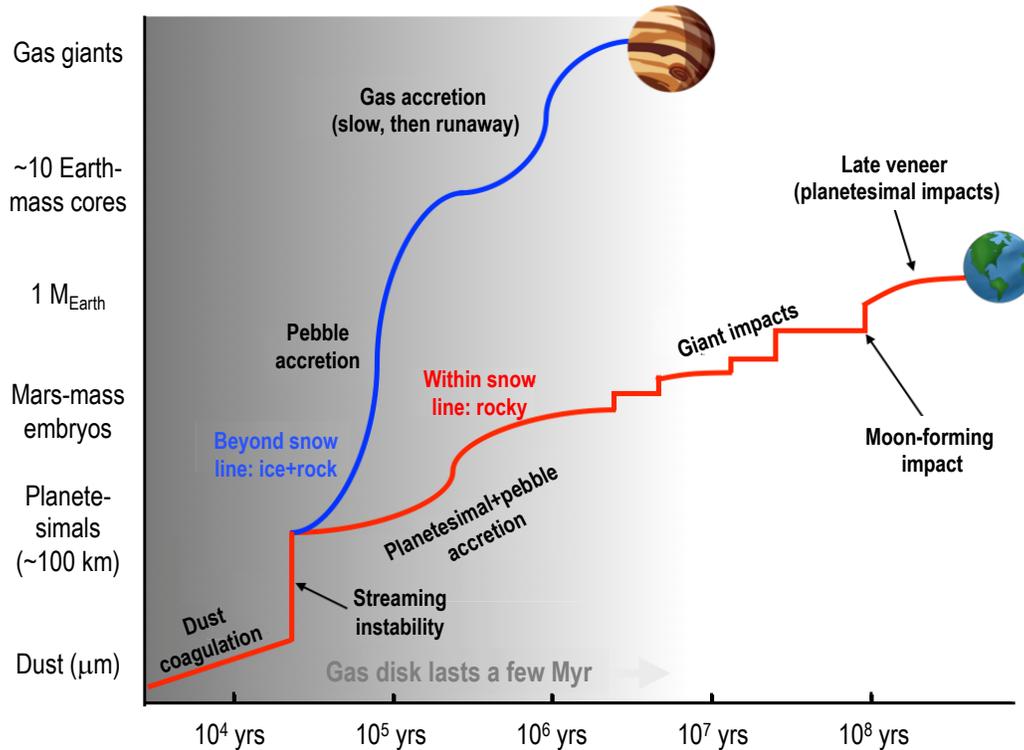


Fig. 8.— A rough summary of the current understanding of the growth history of rocky and gas giant planets, illustrating the various planet formation processes. The cartoon images of Earth and Jupiter are from www.kissclipart.com.

trial accretion occur after the formation of the giant planets (Wetherill 1991, 1996; Chambers 2001; Raymond *et al.* 2006b, 2009, 2014; O’Brien *et al.* 2006; Morishima *et al.* 2010; Fischer *et al.* 2014; Izidoro *et al.* 2015b; Kaib and Cowan 2015). In Fig. 8, late-stage accretion starts after dispersal of the gaseous disk, during the giant impact phase.

The late stage of terrestrial accretion (essentially starting from the “giant impacts” phase shown in Fig. 8) thus starts from a population of roughly Mars-mass planetary embryos embedded in a sea of planetesimals, under the dynamical influence of the already-formed giant planets.

Figure 9 shows an example simulation of the classical model. The compositional gradient in the present-day solar system is assumed to represent the initial conditions for planet formation: inside roughly 2.5 au objects are dry and between 2.5 au and Jupiter’s orbit they have water contents of 5-10% similar to carbonaceous chondrites (Morbidelli *et al.* 2000; Raymond *et al.* 2004).

In the inner disk, there is an effective wave of growth that sweeps outward in time, driven by self-gravity among the growing embryos (Kokubo and Ida 2000). In the asteroid region, eccentricities are excited by Jupiter via secular and resonant forcing. Dynamical friction keeps the most massive planetary embryos on near-circular orbits while planetesimals and smaller embryos often have eccentric and inclined orbits (O’Brien *et al.* 2006; Raymond *et al.* 2006b).

Collisional growth continues for 10-100 Myr as the plan-

ets grow by giant impacts. At the end of the simulation, three terrestrial planets have formed (see Raymond *et al.* 2006b, for details). These include reasonable analogs to Venus and Earth and a planet close to Mars’ orbit that is roughly ten times more massive than the actual planet.

The feeding zones of all three planets included a tail that extended into the outer asteroid belt. The water content of each planet in this simulation was thus sourced from the outer asteroid belt.

The wide feeding zones of the planets in Fig. 9 are a generic feature of late-stage accretion. Eccentricity excitation implies that any planet’s building blocks sample a wide region. Water delivery is, therefore, a robust outcome of classical model-type accretion.

But the classical model has an Achilles heel: Mars. Classical model simulations systematically form Mars “analogs” that are 5-10 times more massive than the real planet (quantified by Raymond *et al.* 2009; Morishima *et al.* 2010; Fischer *et al.* 2014; Izidoro *et al.* 2015b; Kaib and Cowan 2015). The problem is not Mars’ absolute mass but the fact that it is so much less massive than Earth. Accretion tends to form systems in which neighboring planets have comparable masses (e.g., Lissauer 1987). Models that succeed in reproducing the inner solar system invoke mechanisms to deplete Mars’ feeding zone relative to Earth’s (summarized in Fig. 11).

The *Early Instability* model (Clement *et al.* 2018,

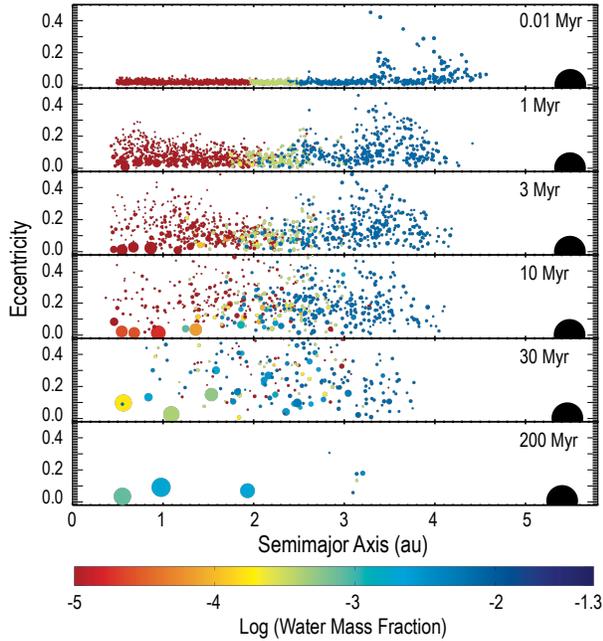


Fig. 9.— Snapshots from a simulation of the classical model of terrestrial planet formation. Jupiter was included from the start, on a low-eccentricity orbit at 5.5 au (large black circle). Almost 2000 planetary embryos are represented by their relative sizes (proportional to their masses^{1/3}) and their water contents, which were imposed at the start of the simulation (red = dry, black = 5% water by mass; see color bar). Three terrestrial planets formed, and each acquired material from beyond 2.5 au that delivered its water. Adapted from *Raymond et al. (2006b)*.

2019a,b) matches the terrestrial planets (including the Earth/Mars mass ratio) while preserving many of the assumptions of the classical model. It assumes that the giant planet instability (sometimes referred to as the Nice model instability because it was developed in the French town of Nice; *Tsiganis et al. 2005; Morbidelli et al. 2007*) took place shortly after the dissipation of the gaseous disk.

Perturbations during the giant planets’ instability act to strongly excite and deplete the asteroid belt and Mars region without strongly affecting the region within 1 au. Simulations match the terrestrial planets’ mass distribution and the rate of success in matching the inner solar system correlates with that in matching the outer solar system (*Clement et al. 2018*).

In the Early Instability model, water is delivered to the growing terrestrial planets from the outer asteroid region in the same way as in Fig. 9. That water would presumably have the same chemical fingerprint as today’s C-type asteroids, represented by carbonaceous chondrites, and thus match the Earth.

The possibility that Earth’s water could be a result of its wide feeding zone therefore rests on the viability of the Early Instability model itself. To date there are three suc-

cessful models that can explain the early evolution of the inner solar system (see *Raymond et al. 2018b*, and also Fig. 11). Future studies will use empirical and theoretical arguments to evaluate these models.

3.2.3. External Pollution

Water may be delivered by a relatively low-mass population of volatile-rich planetesimals that “rain down” onto the terrestrial planet-forming region. In this scenario, the terrestrial planets would have formed predominantly from local rocky material but with a small amount of *external water-bearing pollution*. The difference between this model and the classical model is that the polluting planetesimals are not simply an extension of the planets’ feeding zones but rather were dynamically injected from more distant regions of the planet-forming disk. These water-bearing planetesimals would have been scattered on high-eccentricity orbits by the growth and/or migration of the giant planets during the late parts of the gaseous disk phase.

To date, two mechanisms have been proposed to produce a population of high-eccentricity planetesimals. The first is a general mechanism that applies to every instance of giant planet growth (*Raymond and Izidoro 2017a*). The second is inherently tied to the Grand Tack model (*Walsh et al. 2011a*).

In the core-accretion model (*Pollack et al. 1996*), gas giant planets grow in two steps (see Fig. 8). First they accrete large solid cores of 5 – 20 M_{\oplus} (likely by pebble accretion; e.g., *Lambrechts and Johansen 2012*). Then they accrete gas from the disk. Gas accretion proceeds slowly until a critical threshold is reached (likely the point at which the mass in the gaseous envelope is comparable to the solid core mass), after which accretion accelerates and the planet rapidly grows into a Saturn- to Jupiter-mass planet (e.g., *Lissauer et al. 2009*) and carves an annular gap in the disk (*Crida et al. 2006*).

Figure 10 shows how the growth of gas giant planets affects nearby planetesimals (from *Raymond and Izidoro 2017a*). When a planet such as Jupiter undergoes a phase of rapid gas accretion it destabilizes the orbits of nearby objects. Planetesimals undergo close encounters with the growing Jupiter and are scattered onto eccentric orbits across the solar system. Meanwhile, gas drag acts to damp the planetesimals’ eccentricities. Planetesimals scattered inward can thus become decoupled from Jupiter as their apelia decrease, and be trapped onto stable orbits in the inner solar system (*Raymond and Izidoro 2017a; Ronnet et al. 2018*). Saturn’s growth has a similar effect, although planetesimals must be scattered first by Saturn and then by Jupiter to reach the inner solar system. Because Saturn is thought to have grown later than Jupiter when the planet-forming disk had evolved and was lower in mass than it was during Jupiter’s formation, many planetesimals are scattered inward *past* the asteroid belt to the terrestrial planet region. Many planetesimals destabilized by Saturn may also be captured in Jupiter’s circumplanetary disk (*Ronnet*

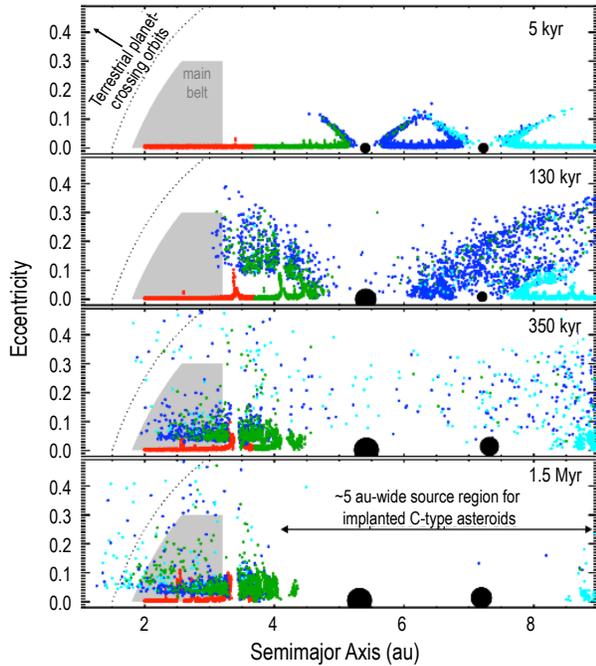


Fig. 10.— Dynamical injection of planetesimals into the inner solar system during Jupiter and Saturn’s growth. This figure shows snapshots of a simulation in which 100-km planetesimals interact gravitationally with the growing gas giants and by gas drag with the disk. Jupiter’s mass was increased from a core to its final mass from 100–200 kyr and Saturn from 300–400 kyr. The colors of planetesimals serve to indicate their starting location. A large number of planetesimals were captured on stable orbits in the outer asteroid belt, providing a good match to the C-type asteroids. Many planetesimals were scattered onto high-eccentricity orbits that cross the growing terrestrial planets’ and may have delivered water to Earth. The source region for implanted planetesimals was from 4 to 9 au in this example, but can extend out to 20 au when migration and the ice giants are considered. From *Raymond and Izidoro (2017a)*.

et al. 2018).

The same population of scattered planetesimals end up crossing the terrestrial planets’ orbits and populating the outer asteroid belt (*Raymond and Izidoro 2017a*). This mechanism naturally explains why carbonaceous chondrites (from C-type asteroids) are a chemical match to Earth’s water.

The balance between planetesimals implanted into the belt and scattering toward the terrestrial zone depends on unknown parameters. The most important parameter is simply the strength of gas drag, which depends on a combination of the planetesimal size and the gas surface density in the inner disk at the time of planetesimal scattering. It is likely that there were many generations of planetesimal scattering into the inner solar system: during Jupiter and Saturn’s growth and possible migration and the ice gi-

ants’ growth and migration. In the example simulation from Fig. 10, planetesimals are implanted from a 5 au-wide swath of the disk. However, this is a *minimum* width, as taking migration and the ice giants into account can extend the source region to past 20 au (*Raymond and Izidoro 2017a*).

The mechanism illustrated in Fig. 10 is generic and applies to any instance of giant planet formation (*Raymond and Izidoro 2017a*). It may thus explain the initial conditions of the classical model. This mechanism has also been shown to be robust to a number of migration histories for the giant planets (*Raymond and Izidoro 2017a; Ronnet et al. 2018; Pirani et al. 2019*).

This mechanism also naturally provides a source of C-types and terrestrial water for the *Low-mass Asteroid Belt* model, another viable model for terrestrial planet formation. The Low-mass Asteroid Belt model proposes that the terrestrial planets did not form from a broad disk of rocky material but rather from a narrow annulus (for details see *Raymond et al. 2018b*, and Fig. 11). In this model, the large Earth/Mars mass ratio is a simple consequence of a primordial mass deficit in the Mars region (*Hansen 2009; Kaib and Cowan 2015; Raymond and Izidoro 2017b*, this would also explain the large Venus/Mercury mass ratio). Perhaps planetesimal formation was simply more efficient at 1 au and 5 au than in between. ALMA has indeed found a number of young circumstellar disks containing rings of dust (*ALMA Partnership et al. 2015; Andrews et al. 2018*). Given that planetesimal formation is only triggered in regions of high dust density (*Carrera et al. 2015; Yang et al. 2017*), it is plausible to imagine that planetesimals also form in rings. The Low-mass Asteroid Belt model can plausibly match the terrestrial planets and asteroid belt and is on the same footing as the Early Instability and Grand Tack models.

The second mechanism of water delivery by external pollution depends on *outward* migration in the framework of the Grand Tack model (*Walsh et al. 2011b; Jacobson and Morbidelli 2014; Raymond and Morbidelli 2014; Brasser et al. 2016*, ; see also Fig. 8). The growing Jupiter would have carved a gap in the gaseous disk and migrated inward in the type 2 regime. Saturn would have grown later farther out, migrated inward and become trapped in mean motion resonance with Jupiter (*Morbidelli et al. 2007; Pierens and Nelson 2008*). Two planets are in mean motion resonance when their orbital periods form the ratio of small integers; e.g., in the 3:2 resonance the inner planet orbits the star three times for every two orbits of the outer planet, at which time the planets re-align. After this point the two planets would have shared a common gap in the disk and tilted the torque balance so as to migrate outward together (*Masset and Snellgrove 2001; Morbidelli et al. 2007; Crida et al. 2009*). This outward migration mechanism operates when two planets share a common gap with the innermost being more massive. Hydrodynamical simulations find that Jupiter and Saturn can migrate outward in the 3:2 or 2:1 resonances (*Masset and Snellgrove 2001; Morbidelli et al. 2007; Zhang and Zhou 2010; Pierens and Raymond 2011; Pierens et al. 2014*). Jupiter and Saturn would thus have

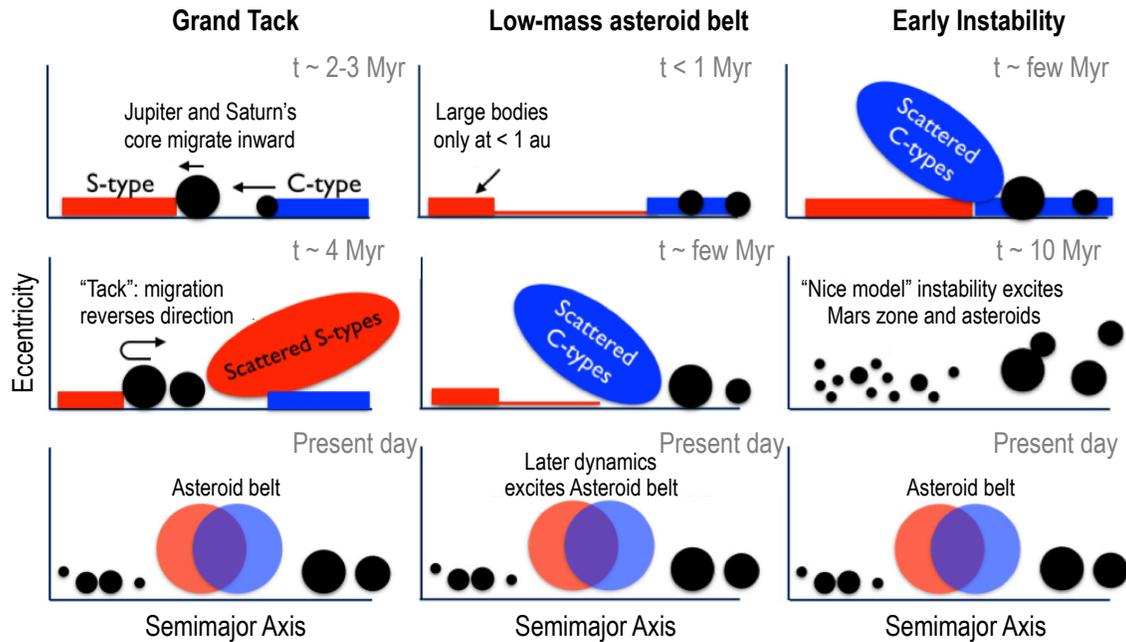


Fig. 11.— Cartoon of the evolution of three models that can match the inner solar system. From *Raymond et al.* (2018b).

migrated outward together until the disk dissipated.

Jupiter’s migration would have dramatically sculpted small body populations (*Walsh et al.* 2011a, 2012). During its inward migration, Jupiter pushed most of the inner rocky material further inward by resonant shepherding (see *Fogg and Nelson* 2005; *Raymond et al.* 2006a), which acted to compress a broad disk of rocky material into a narrow annulus (similar to the one invoked for the Low-mass Asteroid Belt model). A fraction of rocky planetesimals were scattered onto wider orbits, some scattered out to the Oort cloud (*Meech et al.* 2016). At the turnaround point of its migration Jupiter was 1.5-2 au from the Sun (*Walsh et al.* 2011a; *Brasser et al.* 2016). Then, during Jupiter and Saturn’s outward migration the giant planets first encountered the scattered rocky planetesimals and then pristine outer-disk planetesimals. As the giant planets migrated through these small bodies most were ejected, but a small fraction were scattered inward and left behind on stable orbits once the planets migrated past. This mechanism is less dependent on the planetesimal size than the one illustrated in Fig. 10 because the orbits of scattered planetesimals are stabilized by the giant planets migrating away rather than by gas drag. In the Grand Tack model, the surviving planetesimals are trapped in the asteroid belt with a similar orbital distribution to the observed one (*Deienno et al.* 2016).

In the Grand Tack model, water-rich planetesimals are scattered into the terrestrial planet-forming region from beyond Jupiter’s orbit (*Walsh et al.* 2011a; *O’Brien et al.* 2014). The mass in water-delivering planetesimals can be calibrated to the mass in planetesimals trapped in the asteroid belt. Taking into account later depletion of the belt (*Minton and Malhotra* 2010; *Nesvorný* 2015), the mass

in polluting planetesimals is a few to ten percent of an Earth mass. The growing Earth accretes enough water to account for its current water budget (*Walsh et al.* 2011a; *O’Brien et al.* 2014).

External pollution represents a viable scenario for water delivery. Inward scattering of planetesimals is an inevitable byproduct of giant planet formation (see Fig. 10 and *Raymond and Izidoro* 2017a). The Grand Tack model matches a number of characteristics of the inner solar system. The main uncertainty lies in the outward migration mechanism (see *Raymond and Cossou* 2014, for a discussion), which requires that Jupiter remain substantially more massive than Saturn during the entire accretion phase (*Masset and Snellgrove* 2001).

The astute reader may ask themselves how the external pollution mechanism differs from the old comet-delivery model. That model proposed that Earth grew locally and later received its water via a bombardment of comets (e.g., *Delsemme* 1992; *Owen and Bar-Nun* 1995). In contrast with the cometary model, the external pollution model invokes (1) self-consistent, global dynamical scenarios that explain the origin of Earth’s water in the context of models that match the architecture of the inner solar system; and (2) does not invoke comets but rather polluting objects that originate from the same reservoir as C-type asteroids, which match Earth’s D/H and $^{15}\text{N}/^{14}\text{N}$ ratios (comets do not match the Earth’s $^{15}\text{N}/^{14}\text{N}$ ratio; see Fig. 5).

3.2.4. Inward Migration

Orbital migration is a ubiquitous process in planet formation. Given that planets form in gaseous disks, gas-driven migration is simply inevitable once planets reach a

critical mass (Kley and Nelson 2012; Baruteau et al. 2014).

Migration is almost certainly a key process in the formation of so-called *super-Earths* and *sub-Neptunes*, which exist around 30-50% of main sequence stars (Howard et al. 2012; Mayor et al. 2011; Petigura et al. 2013; Mulders et al. 2018). For virtually any disk profile, these planets should have migration timescales that are far shorter than the disk lifetime (e.g., Ogiwara et al. 2015). Models that invoke the migration of growing planetary embryos can quantitatively match the observed super-Earth distributions (e.g., Ida and Lin 2010; Cossou et al. 2014; Izidoro et al. 2017, 2019; Ogiwara et al. 2018).

There is good reason to think that planetary embryos massive enough to undergo long-range migration form past the snow line. Planetesimals may form by the streaming instability most readily just past the snow line (Armitage et al. 2016; Drżkowska and Alibert 2017). Pebble accretion is also much more efficient past the snow line; by the time $10 M_{\oplus}$ ice-rich cores have formed at 5 au, rocky planetary embryos in the inner disk may only reach $\sim 0.1 M_{\oplus}$ (Morbidelli et al. 2015). This fits nicely with our picture of solar system formation, which requires a population of \sim Mars-mass rocky embryos in the inner disk and a handful of giant planet cores in the outer disk.

If embryos large enough to migrate do indeed form past the snow line, then many are likely to be ice-rich. However, if embryos form at the snow line and migrate inward while continuing to accrete, they may only be $\sim 5-10\%$ water by mass, a far cry from the 50% that is often assumed. That assumption is questionable given that the most water-rich meteorites (including both components, the chondrites and matrix) have water-to-rock ratios of ~ 0.4 despite appearing to be outer Solar System objects (Alexander 2019a,b). In addition, while the inward migration of icy super-Earths perturbs the growth of terrestrial planets (Izidoro et al. 2014), it may lead to the formation of very close-in planets that are entirely rocky (Raymond et al. 2018a). By all of these avenues, migration tends to produce planets whose feeding zones are disconnected from their final orbital radii (e.g., Kuchner 2003).

Could inward migration explain the origin of Earth water? Probably not. Multiple lines of (admittedly circumstantial) evidence suggest that the building blocks of the terrestrial planets were roughly Mars-sized (see Morbidelli and Nesvorný 2012). Mars is below the mass required for long-range migration. In addition, if Earth or its building blocks did migrate inward then it is hard to understand why they would have stopped where they did rather than migrating closer to the Sun.

However, migration may indeed play a role in delivering water to Earth-like planets in other systems. This may be particularly important for planets orbiting low-mass stars (see Section 4.1).

4. Discussion

As discussed in Section 3, a number of different scenarios can in principle match the amount and isotopic composition of Earth’s water. However, some of them do not fit in a clear way within a self-consistent picture of the dynamical and chemical evolution of the solar system. On the other hand, other mechanisms are essentially inevitable, as they are simple byproducts of planet formation (for instance, the growth of a giant planet invariably pollutes its inner regions with water-rich planetesimals: Raymond and Izidoro 2017a).

4.1. Evaluation of Water Models

We now evaluate critically the six scenarios from Section 3. We find that the external pollution mechanism is currently the most likely candidate.

While physically motivated, it is hard to see how the two scenarios for local water accretion could fit in a bigger picture of solar system formation. The adsorption of water vapor onto grains struggles because (1) the gas in the inner solar system was likely mainly dry; (2) the D/H ratio of adsorbed water should in principle be nebular, not Earth-like; and (3) the existence of dry chondritic meteorites (e.g., enstatite chondrites) restricts the plausible parameter space for the mechanism to operate. However, it should be noted that the D/H ratio for the primordial mantle material is only an upper limit and it could be lower, or the measurements did not measure the D/H of the original/indigenous water (Hallis et al. 2015), so more measurements are needed.

Earth and its constituent planetary embryos may have accreted primordial hydrogen-rich atmospheres. Oxidation during the magma ocean phase may have produced water (Ikoma and Genda 2006), after which extensive atmospheric loss could have increased the D/H ratio to Earth ocean-like values (Genda and Ikoma 2008). However, it seems a great coincidence for the surviving water on Earth to match carbonaceous chondrites in their D/H ratios. It is also unclear whether this model could explain Earth’s $^{15}\text{N}/^{14}\text{N}$ ratio given that the Nitrogen would have come from a different source.

The Sun’s snow line may have been interior to Earth’s orbit during a significant fraction of the disk lifetime (e.g., Oka et al. 2011; Martin and Livio 2012). However, it seems unlikely that inward-drifting pebbles provided Earth’s water. The age distributions of the two, isotopically-distinct classes of meteorites – carbonaceous and non-carbonaceous – suggest that those reservoirs were kept separate as of ~ 1 Myr after CAIs, and this segregation has been interpreted as being caused by the growing giant planets (perhaps Jupiter’s core) blocking the inward drift of carbonaceous pebbles (Budde et al. 2016; Kruijjer et al. 2017; Desch et al. 2018a). Since the carbonaceous pebbles represent the source of water, it is hard to imagine how they could have delivered water to Earth without producing a population of meteorites intermediate in composition between the two known classes. Yet the ordinary and R chondrites

formed at ~ 2 Myr after CAIs but show signs of having accreted water ice (Alexander *et al.* 2018b). The origin of that ice is hard to understand, and may be linked with pebble recycling in the inner disk or Jupiter’s core acting as an imperfect pebble barrier (e.g., Morbidelli *et al.* 2016).

In the classical model of solar system formation (Wetherill 1992), Earth’s water is a byproduct of its broad feeding zone (Morbidelli *et al.* 2000; Raymond *et al.* 2004, 2007a). However, the classical model cannot easily match the large Earth/Mars mass ratio (e.g., Raymond *et al.* 2009; Morishima *et al.* 2010) and is therefore suspect. The Early Instability model can reproduce Mars’ mass and also delivers water to Earth due to its broad feeding zone (Clement *et al.* 2018, 2019a). Yet the processes that shaped the initial water distribution remain unexplained by such models.

At present, the external pollution model provides the most complete explanation for the origin of Earth’s water. A population of planetesimals on high-eccentricity orbits crossing the terrestrial zone is naturally produced by the giant planets’ growth (Raymond and Izidoro 2017a) and migration (Walsh *et al.* 2011a; O’Brien *et al.* 2014). This fits within the Grand Tack and Low-mass Asteroid Belt models for terrestrial planet formation (see Fig. 11). The same dynamical processes also implant objects into the outer asteroid belt. The objects that delivered water to Earth should then have had the same chemical signature as carbonaceous chondrites, which do indeed provide a good match to Earth’s isotopic composition in terms of water and nitrogen (Lécuyer *et al.* 1998; Marty 2012). The amount of water delivered depends on unconstrained parameters (e.g., the disk properties and planetary migration rates) but plausible values can match Earth. Of course, these dynamical models remain a matter of debate (Raymond *et al.* 2018b). Nonetheless, there are no obvious problems with this delivery mechanism.

Finally, inward-migrating planetary embryos can indeed deliver water to inner rocky planets (or themselves become inner ice-rich planets; e.g., Terquem and Papaloizou 2007; Izidoro *et al.* 2019; Bitsch *et al.* 2019). However, the building blocks of our solar system’s terrestrial planets are likely to have been \sim Mars-mass (see Morbidelli and Nesvorný 2012), below the mass for substantial orbital migration.

4.2. Water Loss Processes

Several mechanisms exist that may significantly dry out planetesimals and planets that were not accounted for in the models presented in Section 3.

The short-lived radionuclide ^{26}Al (half-life of $\sim 700,000$ years) provided a huge amount of heat to the early solar system. As a result, any planetesimals that formed within roughly 2 million years of CAIs would have been completely dehydrated (Grimm and McSween 1993; Monteux *et al.* 2018). In addition, the presence of ^{26}Al can lead to a bifurcation between very water-rich planets with tens of percent of water by mass and relatively dry, rocky planets like Earth (Lichtenberg *et al.* 2019). Because ^{26}Al is

produced in massive stars, its abundance in planet-forming disks may vary considerably (Hester *et al.* 2004; Gounelle and Meibom 2008; Gaidos *et al.* 2009; Lichtenberg *et al.* 2016), leading to a diversity in the water contents of terrestrial exoplanets.

Impacts may also strip planets of water. Ice-rich mantles can be stripped in giant impacts (Marcus *et al.* 2010). Given that the impact impedance of water is lower than that of rock, giant impacts preferentially remove water from the surfaces of water-rich planets (Genda and Abe 2005). Planetsesimal impacts may erode planetary atmospheres (Svetsov 2007; Schlichting *et al.* 2015), causing water loss if a large fraction of planets’ water is in the atmosphere.

Improving our understanding of water loss may be as important as improving our understanding of water delivery.

4.3. Extrapolation to Exoplanets

The bulk of extra-solar planetary systems look very different than our own (see Section 1 and discussion in Raymond *et al.* 2018b). Yet we think that the same fundamental processes govern the formation of all systems. In this section we evaluate which of the mechanisms from Section 3 are likely to be dominant in exoplanet systems.

Our analysis leads to two conclusions. First, we expect water to be delivered to virtually all rocky planets. Any completely dry planets are likely to have *lost* their water. Second, while pebble snow, broad feeding zones and external pollution are likely to play a role, we expect migration to be the dominant mechanism of water delivery. Migration is also the mechanism that should produce planets with the highest water contents. This conclusion is based on overwhelming empirical and theoretical evidence that the population of super-Earths form predominantly during the gaseous disk lifetime, leading to the inescapable conclusion that planet-disk interactions – and therefore orbital migration – must have played a role in shaping this population (e.g., as in the model of Izidoro *et al.* 2017, 2019). Indeed, current thinking invokes migration as one of a handful of essential ingredients in planet formation models (see Raymond *et al.* 2018b).

Imagine a planet growing in the hotter regions of a planet-forming disk, in its star’s habitable zone. Ironically, while a planet in this region can maintain liquid water on its surface (with the right atmosphere), the local building blocks are dry. Given the diversity of water delivery mechanisms, it is hard to imagine such a planet remaining dry. Of course, if water is sourced locally – from adsorption onto grains or from the oxidation of a primordial H-rich envelope – then it will be hydrated anyway. If the planet accretes from a smooth disk of solid material then its feeding zone will widen in time to encompass more distant, volatile-rich bodies. Even if the planet is growing from a ring of material, the snow line moves inward as the gaseous disk cools, such that pebbles can “snow” down and deliver water. Pebble snow can be shut down by the growth of a large outer planet, but that planet would produce a rain of

water-rich planetesimals that pollute the inner rocky zone. A large outer planet might even migrate inward and deliver water in bulk (and perhaps become the ocean-covered seed of a habitable zone planet). Most stars are lower in mass than the Sun (*Chabrier* 2003), with lower luminosities and correspondingly closer-in habitable zones (*Kasting et al.* 1993). Certain factors argue that habitable zone planets around low-mass stars should be drier than around Sun-like stars. In dynamical terms, the snow line is farther away from the habitable zone around low-mass stars (*Kennedy and Kenyon* 2008; *Mulders et al.* 2015a). This would presumably reduce the efficiency of pebble snow and also of external pollution (which is also reduced by the lower frequency of gas giants around low-mass stars; *Johnson et al.* 2007). Since their habitable zones are closer-in, accretion timescales are shorter around low-mass stars (compared with Sun-like stars) and impact speeds higher (*Lissauer and Stevenson* 2007; *Raymond et al.* 2007b). Other factors are ambiguous with regards to water delivery. While fast accretion timescales imply an increase in the efficiency of migration, the masses of planet-forming disks appear to be lower around low-mass stars (*Pascucci et al.* 2016). Low-mass stars are observed to have more “super-Earths” and fewer “mini-Neptunes” than Sun-like stars (*Mulders et al.* 2015b) but it remains unclear how this connects with planet formation and water delivery.

Migration is likely a dominant process in determining planetary water contents. Many models for the origin of super-Earths invoke large-scale migration of large planetary embryos (*Terquem and Papaloizou* 2007; *McNeil and Nelson* 2010; *Ida and Lin* 2010; *Cossou et al.* 2014; *Ogihara et al.* 2015; *Izidoro et al.* 2017, 2019). Given that embryos are thought to form faster past the snow line (by pebble accretion; *Lambrechts et al.* 2014; *Morbidelli et al.* 2015), most of the super-Earths formed by migration should be ice-rich (but see *Raymond et al.* 2018a). Some large embryos may grow close to the inner edge of the disk by accumulating drifting pebbles (*Chatterjee and Tan* 2014, 2015). Embryos that grow large past the snow line before migrating inward have water contents of ten or more percent (*Bitsch et al.* 2019; *Izidoro et al.* 2019), whereas those that grow close-in should be purely rocky. Despite the preferential stripping of icy mantles during giant impacts (*Marcus et al.* 2010), collisions between these two populations will likely maintain the bimodal distribution of very water-rich planets and very dry ones. Planets with intermediate water contents would only form after one ice-rich embryo underwent a series of giant impacts with pure rock embryos.

None of the other water delivery mechanisms is likely to produce planets with more than $\sim 1\%$ water by mass. Pebble snow is susceptible to being deactivated by the growth of any large core on an exterior orbit (*Lambrechts and Johansen* 2014; *Bitsch et al.* 2018). In addition, the pebble flux may drop substantially when the pebble production front reaches the outer edge of the disk, limiting the overall amount of water that can be delivered (*Ida et al.* 2019). The sweet spot for pebble snow may thus be early, before the

growth of large cores and while the pebble flux is high. Very water-rich planets may grow from ice-rich pebbles (*Lambrechts and Johansen* 2012; *Morbidelli et al.* 2015), and these are the planets likely to migrate inward (e.g., *Ormel et al.* 2017; *Bitsch et al.* 2019).

Water contents similar to Earth’s ($\sim 0.1\%$ water by mass) are not detectable with present-day techniques. Our knowledge of the water contents of exoplanets is very limited. Mass and radius measurements exist for dozens of known close-in low-mass planets (e.g., *Batalha et al.* 2013; *Marcy et al.* 2014). These data have revealed a dichotomy between small, solid *super-Earths* ($R \lesssim 1.5 - 2 R_{\oplus}$) and larger, gas-rich *sub-Neptunes* (*Rogers* 2015; *Wolfgang et al.* 2016; *Chen and Kipping* 2017). Some well-measured super-Earths have densities high enough to be scaled-up versions of Earth or even Mercury (*Howard et al.* 2013; *Santerne et al.* 2018; *Bonomo et al.* 2019). However, constraining water contents from density measurements is fraught with uncertainty (e.g., *Adams et al.* 2008; *Selsis et al.* 2007; *Dorn et al.* 2015). The gap in the size distribution of super-Earths (*Fulton et al.* 2017) has been interpreted as an indication that most super-Earths are rocky (*Lopez* 2017; *Owen and Wu* 2017; *Jin and Mordasini* 2018) but there is considerable debate (e.g., *Zeng et al.* 2019). Given measurement uncertainties, the meaning of “rocky” vs “ice-rich” is ambiguous; some models can match the radius gap with planets with anything up to 20% water by mass (*Gupta and Schlichting* 2019).

4.4. What New Measurements are Needed?

What measurements do we need to move forward? As discussed previously, the external pollution mechanism is currently the most likely candidate. However, this still leaves a wide range of possible distances from where the volatiles may have originated. The source location in the disk will depend upon where and when Jupiter’s core formed. The key will be to match the signatures from volatiles in primitive objects that preserve the early solar system record and whose dynamical provenance is reasonably well understood. This region is the “wet” outer asteroid belt. Material scattered into the inner solar system will be both implanted into the asteroid belt, and impact the growing terrestrial planets. While the material that built the terrestrial planets no longer exists, the material scattered inward still exists today in the asteroid belt, and volatiles have been preserved in the outer belt.

Direct evidence for water in the outer asteroid belt stems from the *Herschel* detection of water vapor from Ceres (*Küppers et al.* 2014) coupled with water ice detections on Ceres’ surface by the *Dawn* mission (*Combe et al.* 2016), and a possible H₂O-frost signature on the asteroids 90 Antiope (*Hargrove et al.* 2015) and 24 Themis (*Campins et al.* 2010; *Rivkin and Emery* 2010). Main Belt comets (MBCs) are the primitive representatives of accessible ice from the outer asteroid belt. Orbiting in the outer asteroid belt since the early stages of solar system formation (*Hsieh and Jewitt*

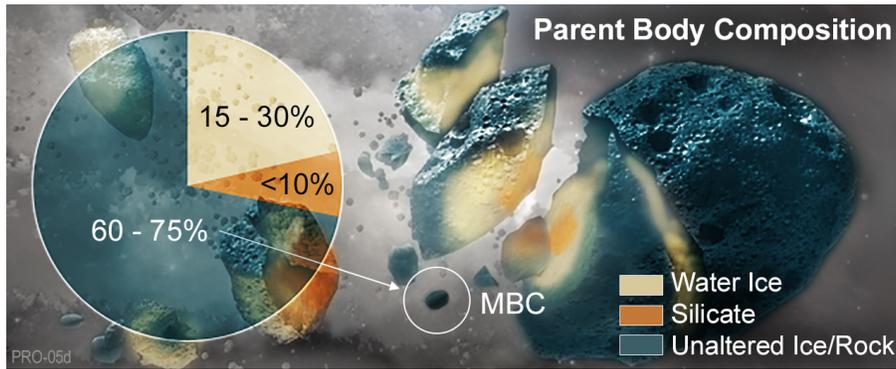


Fig. 12.— Thermal models show that MBC parent bodies preserve unaltered materials throughout 60-75% of the body for their history (*Castillo-Rogez and Schmidt 2010*). MBCs are from this unaltered fraction (*Marsset et al. 2016*).

2006; *Jewitt 2012*), they exhibit comet-like tails, attributed to outgassing of volatiles from ices in their interiors. The ices, preserved by a layer of dust, carry a signature of the early solar system.

All objects whose semimajor axes are less than Jupiter’s, with an orbit dynamically decoupled from Jupiter (*Vaghi 1973; Kresak 1980*), and exhibiting mass loss with a cometary appearance, are termed “Active Asteroids”. They are dynamically unrelated to comets (*Levison et al. 2006; Haghhighipour 2009*). There are 25 currently known. Several causes for their comet-like activity have been postulated, including electrostatic ejection (*Criswell and De 1977*), mass shedding from collisional and radiation torques (YORP) (*Drahus et al. 2011; Jacobson and Scheeres 2011*) rotational instability and volatile sublimation (*Jewitt 2012*).

Only a thermal process, e.g., sublimation, can explain the observed repeated perihelion activity. The twelve believed to be water ice sublimation-driven (seven with repeat activity (*Hsieh et al. 2018a*)) are termed MBCs (*Snodgrass et al. 2017*), of value for their primordial ices. At the distance of the asteroid belt, the interior temperatures are warm enough that only water and its trapped volatiles remain over the age of the solar system (*Prialnik and Rosenberg 2009*). MBC sublimation is believed to be triggered by impacts of meter-sized objects that remove part of the surface layer, allowing heat to reach the ice (*Hsieh et al. 2009; Haghhighipour et al. 2016*). Models predict activity will continue for 100s of orbits, and will show significant fading before ceasing (*Prialnik and Rosenberg 2009*). Conversely, non-MBC active asteroids exhibit very different, short-lived dust structures (*Jewitt 2012; Hainaut et al. 2012; Kleyna et al. 2013*). All attempts to directly detect gas³ have been unsuccessful—unsurprising, given that the detection limit for a 10m telescope is one to two orders of magnitude above the amount of gas required to lift the observed dust. Indeed, Kuiper belt and Oort cloud comets at

the same distance routinely show no spectral evidence for gas, although their dust comae are strong.

MBCs are small (radii < 2 km), with low albedos and with flat featureless spectra in the visible. Most MBCs are related to collisional asteroid families (*Hsieh et al. 2018b*) since this is an excellent way to bring interior ices closer to the surface. For example, the Themis family represents the collisional remnants of an icy protoplanet a few 100 km in size (Fig. 12). A weak or absent hydration signature suggests limited aqueous alteration in the Themis parent interior (*Marsset et al. 2016*), consistent with thermal models predicting a thick, unaltered outer layer of primitive ice and rock (*Castillo-Rogez and Schmidt 2010*). Diversity in the Themis family spectral properties is interpreted as a gradient in the parent body composition, supporting that scenario (*Fornasier et al. 2016*). Stripping of Themis outer layer formed a large fraction of the family members, including the MBCs, without re-processing their volatile content (*Durda et al. 2007; Rivkin et al. 2014, Fig. 12*).

MBCs are samples from the unexplored icy asteroids that are small enough and/or formed late enough to have escaped complete hydrothermal processing and still have primitive outer layers (Fig. 12), unlike Ceres, an icy asteroid that has suffered intensive aqueous alteration (*Ammanito et al. 2016*). An alternate explanation for the origin of some MBCs is that they are primordial planetesimals that never accreted into larger bodies. In both cases, MBCs offer accessible pristine volatiles. Thermal models show that these ices can survive over the age of the solar system due to an insulating dust layer (*Prialnik and Rosenberg 2009; Schorghofer 2008*). Thus, these represent the best source of material from which measurements can help distinguish between solar system formation models and the origin of inner solar system water. The key measurements to make will be to obtain the multiple volatile isotopic fingerprints: D/H in water, ¹⁷O/¹⁶O, ¹⁸O/¹⁶O, ¹⁵N/¹⁴N, and ⁸⁴Kr/³⁶Ar.

The next generation of sub-millimeter telescopes envisioned for the next decade will have 10× the sensitivity and resolution of the exquisite performance of ALMA (*Murphy et al. 2018*). These facilities will be able probe

³H₂O and its more readily observable proxy, CN, a minor species that fluoresces strongly and is dragged out of the nucleus with water as it sublimates.

planet formation inside 10 au (Andrews *et al.* 2018), unveiling the chemistry and structures in the habitable zones in nearby protoplanetary disks (Ricci *et al.* 2018; McGuire *et al.* 2018). Careful isotopic measurements of primitive volatiles in the outer asteroid belt gives us the ability to explore these past processes in our own solar system.

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