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The Formation of the Solar System: A Recipe for Worlds

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This paper summarises the recipe – the raw and processed ingredients plus some of the processes – behind making our solar system 4,600 million years ago. Like a gourmand recipe, the solar system formed from many disparate ingredients, many of these ingredients themselves being the products of complex processes. Thus, to create the habitable solar system we see today required extensive work and processing. However, unlike a food recipe, much of how this happened is poorly understood, although a combination of new observations and analysis is ensuring that progress continues to be made.

Keywords: protoplanetary disk, accretion, planet formation, chondrules, calcium–aluminium-rich inclusions

INTRODUCTION

Scientists through the ages have puzzled over how our planet and solar system formed. This is a challenging endeavour, because the environment at the time of planet formation was completely alien compared to that currently on Earth. Whereas in geosciences the maxim "The present is the key to the past" holds true, it is of limited use when deciphering processes for which there are no equivalent environments on Earth today. However, we can learn about the origins of our solar system from four main strands of evidence:

1. Analysis of meteorites and micrometeorites. Most meteorites derive from minor rocky planets (asteroids) and are relicts from the very earliest times of the solar system. Because they have experienced minimal alteration since their formation, they provide direct testament to the ingredients and environment of those early times, and we can analyse their evidence in laboratories. Some meteorites may also come from comets, which are ice-rich small solar system bodies that enter the inner solar system and begin to outgas (Zolensky and Grady 2018 this issue). Micrometeorites likely derive from comets and asteroids (see *Elements* 2016, v12, n3).

2. Space missions to comets and asteroids. Recent missions (such as the European Space Agency's *Rosetta* mission to Comet 67P/Churyumov–Gerasimenko, the Japan Aerospace Exploration Agency's *Hayabusa* return mission to the "S-type" asteroid Itokawa, and NASA's *Dawn* mission to asteroids Vesta and Ceres) can provide additional data about samples that date from the very earliest times in our solar system. These missions can either provide remote data (such as *Rosetta*) or could be sample-return missions that bring samples to Earth for detailed study (such as *Hayabusa*).

3. Observations of star- and planet-forming regions. With the advent of space telescopes and new generation large-scale telescopes, we are starting to see the actual process of planet formation around other stars in detail. This can provide ground truth for our hypotheses about the formation of our own solar system based on ancient samples. Observational work can allow us to learn about the likely astrophysical context of star formation. For example, Hubble Space Telescope images show that stars often form in clusters, the "stellar nurseries" within the Orion nebula being an example. New images from the Atacama Large Millimeter/submillimeter Array (ALMA) telescope (Fig. 1) show dusty disks during the planet-forming process.

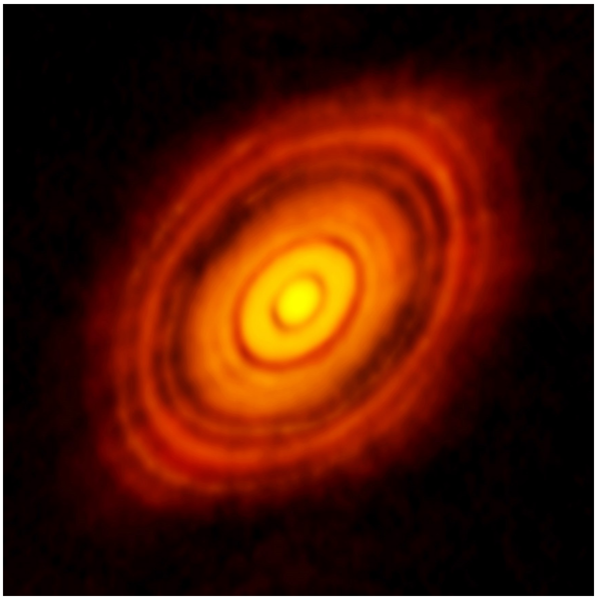

Figure 1 The protoplanetary disk of star HL Tauri (in constellation of Taurus). This image can be interpreted to show a young star and its surrounding disk. The gaps between the dusty rings may indicate where planets have accreted. Photo: taken by the ALMA telescope (Chile), courtesy of ALMA (ESO/NAOJ/NRAO).

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4. Computer simulations. Simulations can put observational and experimental data in context and help us understand what they mean for events that happened in the solar system. Recent times have seen huge advances in the complexity of dynamical models, for example moving from 1-D models to 2-D and even 3-D, all fuelled by the advent of supercomputers.

A consensus view has broadly emerged of general solar system formation. Between the stars is a material called the interstellar medium, an almost empty cold space containing a few atoms, molecules and grains. A denser-than-usual part of this interstellar medium ("molecular core") collapsed under its own gravity. The collapse resulted in many young sibling stars, one example of which was our own young Sun. The Sun was surrounded by a flattened "accretion", or "protoplanetary", disk from which the planets formed. This view of solar system formation from a nebula has been around for centuries: it was postulated by the philosopher Immanuel Kant in his *Universal Natural History and Theory of the Heaven* in 1755 and more formally developed by Pierre-Simon Laplace in his book *Exposition du système du monde* published in 1796. New telescopic images of disk and planet formation, such as that occurring in the protoplanetary disk around star HL Tauri (in the constellation of Taurus) (Fig. 1), demonstrate that this is the mechanism that likely operated in our own Solar System. A genetic connection between the planetary material and the star is bolstered by the similarity in composition of the Sun and of primitive meteorites (e.g. Asplund et al. 2009).

Like a difficult recipe, the solar system formed from a complex list of ingredients that underwent a series of complicated processes. Unlike following a food recipe, where a chef can replicate a process exactly to form the same delicious result every time, the formation of planets entails complex and random events, and so might always turn out different each time. Below are some of the essential known constituents and processes that went into forming our solar system, with a particular focus on how to make minor bodies such as comets.

INGREDIENTS

To make a solar system one needs the following ingredients. These include both the raw ingredients (i.e. material present in the molecular cloud that was parental to the solar system, here called "primordial ingredients") and the processed ingredients (i.e. those that formed, or were altered, in the protoplanetary disk, here called "primitive ingredients").

H, He and Other Gases

The solar system is approximately 98% H and He, along with other gases such as Ar and N, which today are almost entirely contained within the Sun. Like the Sun, the giant planets Jupiter and Saturn are also predominantly composed of these gases. Observations of protoplanetary disks also show that gas is the dominant component. Within meteorites and comets, we can see the fingerprint of primordial gas, trapped gas components, as well as solid condensates from gas, and an often-reduced mineralogy due to mineral solidification in an H_2-dominated environment during formation.

Water

Water was an abundant component of our solar system and the result of its action is found on water-processed materials throughout the solar system. Water is found in all three states and is common in the form of ice beyond the "snow line" – i.e. at distances from the Sun where the temperatures are low. Indeed, ices (including water ice) are the predominant ingredient of cometary materials (e.g. Zolensky and Grady 2018 this issue). The solar system is believed to have an isotope gradient in D/H, with higher values towards the outer disk. To a first approximation, analysis of water in solar system bodies can be used as a fingerprint of the source region (Alexander 2017).

In asteroidal materials, water is predominantly in the form of hydrated minerals – up to ~80% in CM/CI meteorites [i.e. carbonaceous meteorites of the Mighei and Ivuna types] (Howard et al. 2009) – produced by the interaction of liquid water with primitive solar system solids.

Dust

Dust is the solid component of the protoplanetary disk. Dust is dominated by amorphous and crystalline silicates but can also include metals, sulfides, and carbonaceous components (considered separately below). Observations of molecular clouds indicate that the silicates within them are predominantly amorphous and become increasingly crystalline as disk evolution proceeds (van Boekel et al. 2004). The fine-grained (<1 µm) matrix that can make up to ~50% of primitive meteorites provides some insight into this primordial dust (Fig. 2). Amorphous silicate can make up to ~50% of a meteorite's matrix, with crystalline silicates (mainly olivine and pyroxene) and metal and/or sulfides embedded within this amorphous mesh.

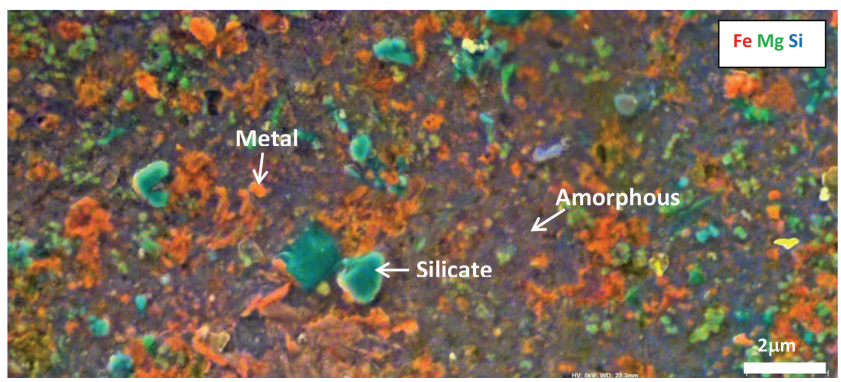

Figure 2 Matrix region of the carbonaceous chondrite CO3 meteorite ALHA77307 (Allan Hills, Victoria Land, Antartica). Element map produced using scanning electron microscopy (FEI Quanta 650 FEG SEM with Bruker Flat Quad 5060F energy dispersive X-ray detector). Iron is in red; magnesium in green; silicon in blue. A purple background shows the amorphous material that makes up most of the matrix. Crystalline silicate grains (green/blue) and fine-grained metal (orange) are embedded in the amorphous mesh. Photo: Courtesy of Epi Vaccaro and Trustees of the Natural History Museum.

Interplanetary dust grains (IDPs) from comets contain an abundant component called "glass with embedded metal and sulfide" (GEMS), a material that is not dissimilar in texture to primordial meteorite matrix. The abundance of GEMS demonstrates that these objects, less than a micron across, are clearly an important pre-accretionary building block for comets. However, it is unclear whether GEMS are formed in the interstellar medium or if they formed within the solar system (Bradley et al. 2014).

Pre-solar grains – minerals that formed around stars ("circumstellar environments") that were ancestors to our Sun – are found in meteoritic matrixes and interplanetary dust particles and include diamonds (although most of these may be solar system in origin); graphite; silicon carbide; silicates; oxides; silicon nitride; carbide;

and metals (e.g. Zinner 2003). Pre-solar grains originated in a variety of dying mass-losing stars that were parents to our Sun.

Organics and Other Carbonaceous Components

Many primitive meteorites host a complex soup of organic molecules that make up to 2% of the total meteorite by mass in CM (carbonaceous chondrite Mighei group) meteorites. Primitive meteorites are rich in a tar-like substance (insoluble organic matter) that is composed of very complex aromatic (ring) units of carbon, called polyaromatic hydrocarbons (PAHs). Primitive meteorites also contain an enormous range of soluble organic molecules. The most abundant of these are carboxylic acids, but there are also amino acids and sugars. The organic components are difficult to observe in situ within meteorites, although Nakamura–Messenger et al. (2006) identified organic globules in the Tagish Lake meteorite that were almost certainly primordial disk components. Indigenous aliphatic organic compounds have also been detected in the Ceres asteroid by NASA's *Dawn* mission (De Sanctis et al. 2017) and in moons of the outer planets. An array of organics has also been found in comets (Yabuta et al. 2018 this issue).

Chondrules and Refractory Inclusions

Chondrules and refractory inclusions are not primordial ingredients but are produced by processes operating in the protoplanetary disk. Chondrules are rounded silicate-rich objects that are common in primitive (unmelted) meteorites called chondrites (Fig. 3). Chondrules have also been found in samples returned from NASA's *Stardust* mission to Comet Wild 2 (Zolensky and Grady 2018 this issue). Meteorites can be composed of up to 80% chondrules by volume. Chondrules are typically ~50 µm to 1 mm in diameter and have melted (igneous) textures, indicating they were once fully or partially molten. Some authors suggest that chondrules have a chemistry complementary to their associated fine-grained matrix, suggesting the two components are genetically linked and formed from the same reservoir (e.g. Palme et al. 2015).

Refractory inclusions, including calcium–aluminium-rich inclusions (CAIs), are inclusions found in some carbonaceous chondrites that are enriched in highly refractory elements, i.e. those elements that are hardest to volatilise: Ca, Al, Ti, the rare-earth elements (REEs) and so on. Refractory inclusions can have fluffy or compact textures, indicating formation by condensation or melting respectively, at a very early point in solar system history (see below).

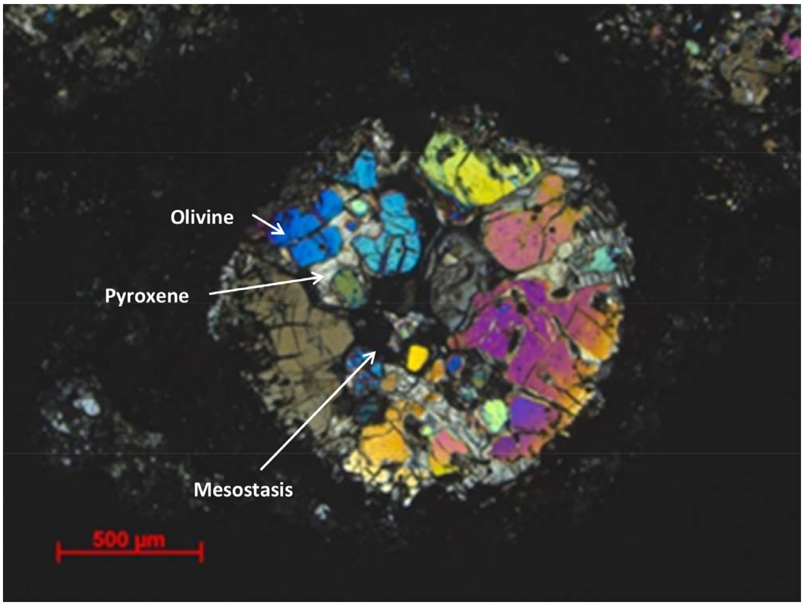

Figure 3 Chondrule from the Al Rais (Saudi Arabia) carbonaceous chondrite CR2 meteorite (optical microscope under cross polars). Field of view is approximately 1 mm. This rounded porphyritic chondrule is composed of blocky olivine crystals surrounded by pyroxene within a fine-grained mesostasis (last-formed material). Photo courtesy of Trustees of the Natural History Museum.

METHOD

It is difficult to write a foolproof method for making a solar system (let alone our solar system) because solar systems are much more complex than even the finest award-winning dish. However, the following processes have left their imprint in solids dating from our early solar system, and so must have played an important role:

Thermal Processes

There is evidence from meteorites that some material condensed from a very hot gas to a solid. The clearest evidence for this process comes from CAIs that have fluffy, porous textures suggesting condensation. The presence of such objects demonstrates the presence of a cooling, reducing gas (relative to chondrules and Earth), and much of the mineralogy of CAIs can be explained by the condensation of a gas of solar (or approximately solar) composition at temperatures of around 1,800–2,000 K. This produces a suite of refractory minerals that are mainly oxides and silicates of Ca, Al and Ti, including spinel, melilite, perovskite, hibonite and corundum (Ebel 2006). Other objects with a condensed texture include amoeboid olivine aggregates, so-called because of their highly irregular shapes which have a CAI-like core and are surrounded by olivine.

The major component of most chondrites are chondrules. Chondrules show that melting was a commonplace process in the early solar system, at least in some locations. This is a notable observation, because a melt is not stable under typical solar nebula conditions unless the pressures or dust:gas ratio is locally elevated – e.g. dust enrichment of around 100× (Ebel 2006). In addition, the abundance of sodium in olivine phenocrysts and the absence of Rayleigh-type isotope fractionation in a series of elements (e.g. Fe, K) suggests that chondrules formed under very high dust pressures. To form chondrules requires a high-energy process to have operated in the protoplanetary disk. The nature of this process is unclear: shock waves and planetesimal collision being strong contenders (Connolly and Jones 2016).

Transport

Transportation of material around protoplanetary disks is a key process. The general direction of travel would have been inwards because materials were accreted by gravitational attraction into the growing Sun. In addition, grains tend to settle towards the midplane of the disk. However, turbulent mixing in the disk ensures that movement is not simple. Material returned from NASA's *Stardust* mission to comet Wild 2 contains fragments of high-temperature minerals: chondrules and CAIs (Zolensky and Grady 2018 this issue). Comets originate in the outer solar system where conditions are cold and there is not likely to have been enough energy to create conditions necessary for the formation of these objects. Thus, the high-temperature minerals found in comets were probably transported from the inner to the outer solar system after their formation. This provides observational evidence for outward transport as a common process in disks. Ciesla (2007) showed that outward transport of material to the comet-forming regions is possible, especially around the midplane of the disk.

Irradiation

Young stellar objects have strong X-ray emission, several orders of magnitude higher than in stars that have settled into their middle age. This was also true of our young Sun. Magnetic fields accelerate charged particles which then irradiated solids, and the effects of this process can be seen in the isotope composition of some early solar system solids, especially in CAIs that likely formed near the Sun. Some CAIs show variable amounts of the irradiation-formed radioactive isotope ^{10}Be that has now decayed to the daughter product ^{10}B (McKeegan et al. 2000), demonstrating that these host CAIs formed during the earliest and most active stage of stellar evolution. In addition, recent work has shown that some, but not all, CAIs contain an excess of ^{50}V, thought to have formed by cosmic irradiation of early solids (Sossi et al. 2017). Modelling the level of this observed isotope anomaly suggests that excess ^{50}V formed from irradiation of refractory dust at 0.1 astronomical units (AU) for less than 300 years (Sossi et al. 2017).

Irradiation can also affect the large-scale structure and evolution of disks by a process called photo-evaporation. This occurs when high-energy radiation ionises gas and causes it to disperse. Photo-evaporation from the star is observed to be an important process in young stars and in planetary systems and is one way in which a protoplanetary disk is processed and eventually removed after the planets have accreted from it (Williams and Cieza 2011).

Magnetism

Magnetism is an important force in young star systems, perhaps driving accretion onto the star and generating turbulence in the disk, which is thought to be critical to the formation of planets. The magnetic field can originate from the central star, from planetesimals that have differentiated to make an iron core or be generated by shear motion of the nebular gas itself. Recent work has shown that the magnetic field of the solar nebula has been recorded in meteoritic components (Fu et al. 2014). At the time the protoplanetary disk existed, the nebular field strength at approximately 1 AU was within an order of magnitude of the Earth's surface magnetic field (10–100 mT) and is expected to be lower in the outer solar system. Therefore, palaeomagnetic measurements can potentially be used as an indicator of where in the solar system an object formed.

Accretion

Accretion is thought to progress in three stages. First, the coagulation of dust at the disk midplane to form small (kilometre sized) planetesimals. Second, the collision of these objects to form planetary embryos. Third, runaway growth that is enabled by gravitational attraction. The coagulation stage may have been helped by electrostatic forces, fluffy-shaped particles, or by organic material acting as glue. Turbulence in the disk may act to help enable accretion. Whereas the accretion from dust to planets is typically described in this stepwise fashion, evidence from meteorites shows that it was not a systematic progression. For example, planetesimals that were large enough to differentiate formed at the same time as chondrule and CAI formation (Kleine et al. 2009). Models of accretion can mostly explain broad geochemical observations, including the abundance of water on Earth (Rubie et al. 2015).

Pebble Accretion

A longstanding issue in the formation of the planets is how the gas giants formed. They are enveloped in hydrogen and helium gas, presumably accreted from the protoplanetary disk. This would require them to form a substantial core before the gas dissipated after a few million years, but how they could grow quickly enough is not well understood. Growth by collisions between planetesimals would take too long. The pebble accretion model, proposed by Lambrechts and Johansen (2012), overcomes this problem. They proposed that the accreting material was dominated by pebble-sized objects (centimetre- to metre-size) that are slowed down by a headwind of the disk gas. This makes them easier to accrete onto the planetesimals and greatly enhances their rate of growth. This process is now understood to operate not only in the case of giant planet formation but for smaller bodies as well.

Planet Migration: The Grand Tack

Two notable features of the present-day solar system are that the planet Mars is rather small and that the asteroid belt contains less mass than expected. In 2011, Walsh et al. proposed a model to explain these observations. In this model, interactions between the nebular gas and the giant planets caused them to migrate inwards towards the Sun within the first few million years of solar system formation. Jupiter eventually reached a point between the present orbits of Earth and Mars. Jupiter and Saturn then became locked into an orbital resonance that caused them to move back outward, until the gas in the disk dissipated. The model has been named "The Grand Tack" because, like the sailing manoeuvre, the planets moved through the wind. This giant-planet movement had the effect of clearing out much of what is now the asteroid belt and suppressing the growth of Mars. On the outward part of the giant planets' journey, minor bodies from the outer solar system would have become scattered into the inner solar system to form the asteroid belt that we see today, which is composed of a range of compositions from inner-planet-like to volatile-rich outer solar system material.

Planet Migration: The Nice Model

A final major process that has affected the inner solar system is the Late Heavy Bombardment. A disproportionate number of the large craters on the lunar surface date from around 3.9–4.1 Ga (Bottke et al. 2012). This may be explained by the "Nice Model" (Tsiganis et al. 2005). In this model, a second period of giant-planet migration occurred when the huge primordial Kuiper Belt (see Zolensky and Grady 2018 this issue) exchanged angular momentum with the planets, causing a violent instability that forced Jupiter inwards and the other planets outwards. This event disrupted the orbit of material in both the Kuiper Belt and the asteroid belt, causing some of the minor bodies to fall into the inner solar system and impact the terrestrial planets.

RECOMMENDED PREPARATION AND COOKING TIME

The timescales involved in forming our solar system can be measured using radioactive dating schemes. The most commonly used method is a chronometer of the now-extinct isotope ^{26}Al. Aluminium-26 has a half-life of 0.717 My. In very ancient solar system objects, such as CAIs, an excess of its daughter isotope, ^{26}Mg, is found in minerals with high Al/Mg, demonstrating that ^{26}Al originally existed in the early solar system. Plotting $^{26}Mg/^{24}Mg$ as a function of $^{27}Al/^{24}Mg$ allows a measurement to be made of ^{26}Mg excess/^{27}Al = initial $^{26}Al/^{27}Al$. Assuming that the initial ratio of radioactive ^{26}Al to stable ^{27}Al($^{26}Al/^{27}Al$) was originally homogeneous, then this initial ratio can be used as a fine-scale chronometer of early solar system events. Unaltered CAIs typically have the same $(^{26}Al/^{27}Al)_{initial}$ of ~5×10^{-5}. Chondrules can show lower and more variable levels of $(^{26}Al/^{27}Al)_{initial}$, typically ~0.5–$1 \times 10^{-5}$. Some of this variability may be due to later isotopic disturbance of daughter magnesium, but the difference between CAIs and chondrules is very clear. Looking only at the most primitive chondrites, the timespan for chondrule formation might in fact be mainly within 0.4 My for a single chondrite group (Kita and Ushikubo 2012). The distinct difference in initial $^{26}Al/^{27}Al$ between CAIs and chondrules could be interpreted as due to a 2 My gap in formation time between the two components. Alternatively, $^{26}Al/^{27}Al$ may not have been homogeneous in the early solar system, but instead may have been initially higher in the CAI forming region. In this case, the difference between chondrules and CAIs has no chronological significance (Larsen et al. 2011).

The radioactive isotope ^{182}Hf (which decays to ^{182}W, with a half-life of 8.9 My) can also be used as a chronometer, using a similar principle to the ^{26}Al system. Data on the Hf–W decay system suggest that silicates and metal fractionated from each other during chondrule formation, and this event occurred in CV [carbonaceous chondrite Vigarano group] meteorites at 2.2 ± 0.8 My after CAI formation (Budde et al. 2016), a result that provides a more robust age than ^{26}Al because initial isotope heterogeneity is unlikely. However, this technique relies on the measurement of many chondrules together and so individual ages cannot yet be ascertained.

Lead–lead dating has also been applied to CAIs and chondrules. This technique has shown that CAIs are very ancient (4.567 Ga), and chondrules started to form at the same time and continued for approximately 3 My (Connelly et al. 2012). A special group of meteorites, the CBs [carbonaceous chondrites of the Bencubbin group], contain chondrules that formed at the same time as each other and approximately 5 My after CAI formation (Fig. 4). The CBs are thought to have formed by a single impact event (Krot and Nagashima 2017). The absence of matrix in CB chondrites indicates that the protoplanetary disk had cleared by this time, giving a final bookend to the lifetime of the disk.

Observations of disks that are in the process of being cleared around young stellar objects provides another mechanism for investigating timescales of planet formation. Around half of disks have dissipated by 3 My, although their age ranges from around 1–10 My (Williams and Cieza 2011 and references therein). The solar system, therefore, appears not unusual in having a disk lifetime on the order of a few million years.

FINAL TASTING NOTES

There is near consensus on a model of planet formation that involves accretion from a protoplanetary disk connected to a star. However, not all the details of how this occurs are understood, and there is debate in several areas of planet formation research. There are many outstanding puzzles, including how chondrules formed and how planets migrated. Our nebular theory of planet formation explains why we see rocky inner planets and outer giant planets. On the other hand, the increasing body of exoplanet observations suggests that this formation is atypical. Gas giants are commonly located close to their parent star. Is this due to planet migration models, such as those proposed for our own early history? And why has the outcome been different to that of own planetary system? Is this due to an observational bias? Over the coming years, the explosion of data for exoplanets will hopefully help us understand our own solar system and whether it requires a unique formation mechanism.

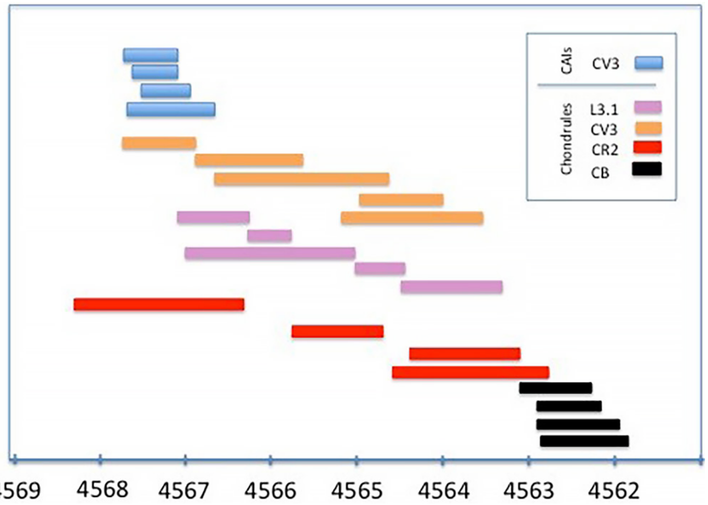

Figure 4 A summary of Pb–Pb ages obtained for primitive components (chondrules and calcium–aluminium inclusions, CAIs) from unaltered meteorites. CAIs formed more or less simultaneously, 4,567–4,568 Ma. Chondrules appear to have formed over several millions of years. The youngest chondrules are from carbonaceous chondrite CB meteorites and probably formed by impact processes. Data from Brennecka et al. (2015 and references therein).

There is a need for a new generation of space missions to minor bodies in the solar system. The JAXA mission *Hayabusa2* to asteroid Ryugu and the NASA *OSIRIS-REx* mission to asteroid Bennu are already in flight. Both plan to visit a primitive asteroid and return samples to Earth, which will be an invaluable opportunity to learn more about the processes that shaped our solar system. Ultimately, a sample return from a cometary nucleus would provide the best information about the processes that shaped our planetary system 4.6 Gy ago, because comets likely preserve the best evidence for these primordial processes.

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