The formation of the solar system

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Abstract. The solar system started to form about 4.56 Gyr ago and despite the long intervening time span, there still exist several clues about its formation. The three major sources for this information are meteorites, the present solar system structure and the planet-forming systems around young stars. In this introduction we give an overview of the current understanding of the solar system formation from all these different research fields. This includes the question of the lifetime of the solar protoplanetary disc, the different stages of planet formation, their duration, and their relative importance. We consider whether meteorite evidence and observations of protoplanetary discs point in the same direction. This will tell us whether our solar system had a typical formation history or an exceptional one. There are also many indications that the solar system formed as part of a star cluster. Here we examine the types of cluster the Sun could have formed in, especially whether its stellar density was at any stage high enough to influence the properties of today's solar system. The likelihood of identifying siblings of the Sun is discussed. Finally, the possible dynamical evolution of the solar system since its formation and its future are considered.

1. Introduction

For decades the solar system was assumed to be the prototype for planetary system formation. With the detection of over a thousand confirmed exoplanets and many more candidates, it has

become apparent that many planetary systems exist that differ substantially in their structural properties from our solar system. Nevertheless the formation of the solar system is still of special interest for several reasons. First, it is only for the solar system that we can directly examine material that is left over from the formation process in the form of meteorites. Second, only for the solar system do we have detailed structural information about the entire system including its smaller bodies. Last but not least, it is only for the solar system that we know for sure that life exists.

The three major sources about the formation of the solar system are meteorites, the present solar system structure and contemporary young planet-forming systems. We start by reviewing the current status of meteorite research concerning the chronology of early solar system formation including the formation of the terrestrial planets in section 2. In this context the question of the origin of short-lived radioactive nuclei in these meteorites is of special interest. Some of these can only be produced in supernovae events of high-mass stars - different possibilities are discussed in section 3.

Other sources of information are young stars surrounded by accretion discs from which planetary systems might form. In section 4 the properties of these discs - masses, gas content and chemical composition - are discussed. Estimates of the life times of these discs are given and the consequences for planet formation scenarios are discussed. Section 5 provides a closer look at the different stages of planet formation. Starting from dust grains, then considering pebble-sized objects to planetismals the current state of research is presented. This is followed by the final step in which planets form.

Many of these young systems are part of a cluster of stars. There are several indications that our own solar system also formed as part of a star cluster. Section 6 gives the arguments for such an early cluster environment and discusses the possibilities of finding today stars that formed in the same cluster as our Sun did. Not only the location and masses of the planets but also those of the asteroid and Kuiper belt are characteristics of our solar system that might potentially give clues to its formation. In section 7 the early dynamical evolution of the Kuiper belt is illustrated. Possible scenarios for the late heavy bombardment between 4.0 and 3.7 Gyr ago are discussed. It is still an open question to what degree the solar system characteristics changed since its formation and how stable the solar system is in the long-run. The likely long-term evolution of the solar and other planetary systems is discussed in section 8. This is followed by a summary in section 9.

First, we look at the information that meteorites give about the formation of the solar system. In order to do so a relative age dating of these meteorites is necessary.

2. The meteorite record of early solar system evolution

2.1. The significance of meteorites

Studying meteorites from our solar system is the only way to directly constrain timescales of its protoplanetary disc evolution. Most meteorites are older than 4.5 billion years and originate from the asteroid belt. The asteroid belt between Mars and Jupiter provides the only vestige of

the planetesimals which were the first larger objects in the protoplanetary disc that provided the building materials for the larger planets. Simulations indicate that it is most likely that the larger planets formed via collisions of such first generation planetesimals (e.g. Wetherill 1990, Chambers 2003). The different groups of meteorites sample these first generation planetesimals and cover the different evolutionary steps of early solar system evolution in great detail. In general, three major groups of meteorites can be distinguished. Chondrites represent unprocessed, brecciated early solar system matter, whereas differentiated meteorites such as achondrites and iron meteorites originate from asteroids that have undergone melting and internal differentiation. These asteroidal melting events were triggered by either decay of short-lived ^{26}Al or by impact events. Due to the short half life of ^{26}Al (0.7 Myr), the first heating mechanism is confined to the first 5 million years of solar system evolution.

2.2. Chondrites and their components

The oldest dated solar system matter are Ca, Al-rich inclusions (CAIs) in chondritic meteorites that have been dated by the U-Pb method to 4.567-4.568 billion years (Amelin et al. 2002, 2011; Bouvier et al. 2007). CAIs are an important anchor point to constrain the abundance of significant short-lived nuclides such as ^{26}Al or ^{182}Hf at the beginning of the solar system. In addition to the long lived U-Pb chronometer, short-lived nuclides with their half-lifes of less than 100 million years enable dating of meteorites and their components at an age resolution as low as several tens of thousands of years. Based on combined U-Pb and Al-Mg chronometry, the ages of chondrules, a major component of chondrites, has been constrained to as late as up to 4 million years after solar system formation (e.g. Bizzarro et al. 2004; Villeneuve et al. 2009). It is currently contentious, as to whether there is a circa 1.5 million years age gap between the formation of the first CAIs and the formation of the first chondrules (see Villneuve et al. 2009; Amelin et al. 2011; Larsen et al 2011; Connelly et al. 2012). There is, however, now consensus that the undifferentiated asteroidal parent bodies of chondrites themselves accreted ca. 2-4 million years after the beginning of the solar system (e.g. Bizzarro et al. 2005; Kleine et al. 2008). Because of their younger accretion ages, chondrites escape internal heating triggered by ^{26}Al (Trieloff et al. 2003, Henke et al. 2013), and thus they preserved their pristine structure.

2.3. Differentiated asteroids

Recent high precision dating using Hf-W and Al-Mg chronometry has shown that some differentiated meteorite groups do in fact predate formation of chondrites. Beside CAIs, some groups of magmatic iron meteorites that represent the cores of differentiated asteroids have been shown to constitute the oldest solar system objects (Kleine et al. 2005). If corrected for cosmic ray exposure, magmatic iron meteorites can be shown to have differentiated within the first 2 million years of solar system history, and their asteroidal parent bodies must have accreted earlier than 0.5 million years after solar system formation (Kruijer et al. 2013, 2014; Wittig et al. 2013). Some older groups of achondrites that sample the outer silicate portion of differentiated asteroids differentiated only slightly later than iron meteorites. The particularly

pristine group of angrites (achondrites consisting mostly of the mineral augite) is inferred to have differentiated by around 3-5 million years after the CAIs (Larsen et al. 2011, Brennecka & Wadhwa 2012; Kleine et al. 2012). Likewise, achondrite groups such as acapulcuites, eucrites, and winonaites as well as non-magmatic iron meteorites differentiated in the time interval between 3-5 million years after solar system formations, with inferred accretion ages between 1 and 2 million years after solar system formation (Schulz et al. 2009, 2010).

2.4. The new early solar system chronology

In summary, there is now clear evidence from short-lived nuclide and long-lived U-Pb chronometry that CAIs are the oldest solar system objects, followed by magmatic iron meteorites (differentiation of 1-2 million years after solar system formation) and most achondrite groups and non-magmatic iron meteorites (differentiation 3-5 million years after solar system formation). Differentiation of these asteroidal bodies was likely driven by internal heat sources, with decay of ^{26}Al being the most important one. The parent asteroids of chondrites accreted much later (2-4 million years after solar system formation) than those of the differentiated asteroids (less than 2 million years after solar system formation). It is therefore likely that the chondritic parent bodies did not undergo internal differentiation, because the heat supply from short-lived nuclides such as ^{26}Al was insufficient, or, alternatively, their parent body size was too small. Alternatively, undifferentiated chondrites may sample the outer layers of planetesimals that differentiated in their interiors.

2.5. Age of the inner terrestrial planets

The larger rocky planets in the inner solar system formed much later than the small asteroids, at timescales of tens of millions of years. Hf-W systematics in terrestrial samples and chondrites constrain the age for the Earth's growth to at least 38 million years (Kleine et al. 2002, Yin et al. 2002; Knig et al. 2011) and probably as late as 120 million years after solar system formation (Allegre et al. 2008; Rudge et al. 2010). There are fewer indicators to constrain the age of Mars, but estimates reach from 2 to 10 million years after solar system formation (Nimmo & Kleine 2007; Dauphas & Pourmand 2011). The uncertainties of these estimates originate from the parameters that are used to model planetary growth and internal differentiation into metal cores and silicate mantles. The small size of Mars, for instance, has been explained by radial migration of Jupiter, suggesting that Mars represents a starved planet that could not accrete further because of interaction with Jupiter (Walsh et al. 2011).

For constraining the age of the Earth, the Moon-forming giant impact event is of great importance, and physical models explaining the formation of the Moon have dramatically changed over the past years (e.g. Canup & Asphaug 2001; Cuk & Stewart 2012; Canup 2012). Likewise, the Hf-W and U-Pb chronometry of Earth's formation has undergone significant reinterpretation. Most earlier studies agreed that both the Hf-W and U-Pb chronometers date segregation of the Earth's core during the final stages of Earth's accretion (e.g. Allegre et al. 2008; Rudge et al. 2010, Wood & Halliday 2005). A combination of experimental and geochemical studies now rather argue that volatile elements such as Pb were delivered

late to the growing Earth, implying that the U-Pb systematics of the Earth's silicate mantle bear no chronological significance (Albarede 2009; Ballhaus et al. 2013; Marty et al. 2012; Schönbächler et al. 2010).

The geochemical and isotopic inventory of meteorites provides a unique chronological record of early solar system evolution. It took only less than one million years after condensation of the first solid matter to form the first generation of planetesimals. These planetesimals underwent internal heating between 1 and 4 million years after solar system formation, largely caused by ^{26}Al decay, triggering their differentiation into metal cores and silicate mantles. The parent asteroids of undifferentiated chondritic meteorites formed 1-2 million years later, and therefore these bodies did not differentiate. Formation of the larger terrestrial planets in the inner solar system occurred via collision of smaller asteroidal bodies. The timescales involved in planetary growth are in the order of tens of million years, with Mars being a possible exception due to gravitational interaction with nearby Jupiter. There is growing evidence, that the volatile element inventory of the inner solar system was added late, i.e. during the last stages of planetary growth.

3. The origin of short-lived radionuclides

Chondrites have not endured any geological activity since they formed during the first million years of our solar system. As such, they record physical processes in the solar protoplanetary disc (SPD) but also of the molecular cloud stage, which preceded the formation of the proto-Sun (Wadhwa et al., 2007).

Chondrites are made of CAIs, chondrules and iron-nickel metal. All these components are cemented by a fine-grained matrix (Fig. 1). A key property of chondrites is the past presence within their components of short-lived radionculides (SLRs). SLRs are radioactive elements, which have half-lives, $T_{1/2}$, smaller than 200 Myr and were present in the early solar system (Russell et al., 2001). Though they have now decayed, their past presence in chondrites and other meteorites is demonstrated by excess of their daughter isotopes.

3.1. Astrophysical context

Since 1962 and the discovery of ^{129}I ($T_{1/2}$ = 15.7 Myr), a long list of SLRs has been identified in meteorites (see the Table of Dauphas & Chaussidon (2011)). SLRs are important because they can potentially help to build an early solar system chronology and are the most likely heat source of the building blocks of planets, planetesimals (Wadhwa et al., 2007). In addition, they can help decipher the astrophysical context of our solar system formation. In other words, assuming the Sun was born as most stars in a (Giant) Molecular Cloud, elucidating SLRs' origin is the only tool to trace back what was the relationship of the Sun with other stars born in the same molecular cloud.

The presence in the early solar system of SLRs having the longest half-lives is not surprising. Similarly to stable isotopes they have been produced in the interior of stars, which have preceded our Sun in the Galactic history and were delivered to the Interstellar Medium
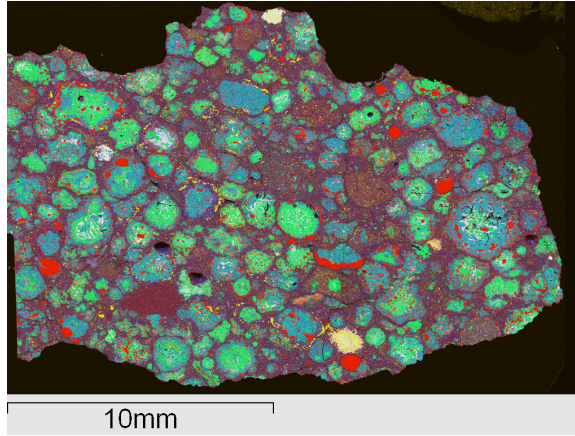
Figure 1. Composite false colour chemical map of the interior of the Renazzo chondrite: aluminum (white), magnesium (green), silicion (blue), calcium (yellow), iron (red). Chondrules are the abundant Mg- and Si-rich objects, CAIs are the rare yellow white inclusions and iron-nickel metal are the red grains. Credit: Anton Kearsley (NHM London).

(ISM) by supernova (SN) explosions and massive star winds. Their abundance is roughly in line with Galactic evolution models (Meyer & Clayton, 2000). The presence of SLRs with shorter half-lives ($T_{1/2} \lesssim 10$ Myr) is more difficult to understand because their half-life is comparable or smaller than the typical timescales of star formation processes (Williams, 2010). Obviously, constraining the origin of SLRs depends also on their initial abundance, which is not always clearly known.

Some SLRs have been synthesised via the irradiation of the SPD gas/dust by proto-solar cosmic-rays (Chaussidon et al., 2006). As we saw in section 2 this is especially the case of ^{10}Be ($T_{1/2} = 1.4$ Myr) whose abundance in CAIs is variable (Gounelle et al., 2013). Independent evidence for early solar system irradiation is given by the variable and intense X-ray emission of protostars (Feigelson, 2010). Other SLRs such as ^{36}Cl ($T_{1/2} = 0.3$ Myr) or ^{41}Ca ($T_{1/2} = 0.1$ Myr) could also have been produced by irradiation according to some models (Gounelle et al., 2001; Duprat & Tatischeff, 2007; Leya et al., 2003). We note that the situation for these SLRs is complicated by the fact that their initial abundance in the solar system is not well constrained (Liu et al., 2012b).

3.2. Special role of ^{26}Al and ^{60}Fe

Aluminium-26 ($T_{1/2} = 0.72$ Myr) and iron-60 ($T_{1/2} = 2.6$ Myr) are probably the SLRs, which have attracted the most attention during the last decade. Iron-60 is too rich in neutrons to be produced by irradiation processes (Lee et al., 1998). As ^{60}Fe is absent from massive star winds, its only possible source in the early solar system is - at least one - supernova, which is known to produce large abundances of that SLR (Wang et al., 2007). Because the initial abundance of ^{60}Fe has long been considered to be elevated (^{60}Fe/^{56}Fe $\sim 10^{-6}$ (Tachibana & Huss, 2003)), the presence of ^{60}Fe has been interpreted as evidence for a nearby supernova (Hester et al., 2004). According to supernova nucleosynthetic models, the SN had
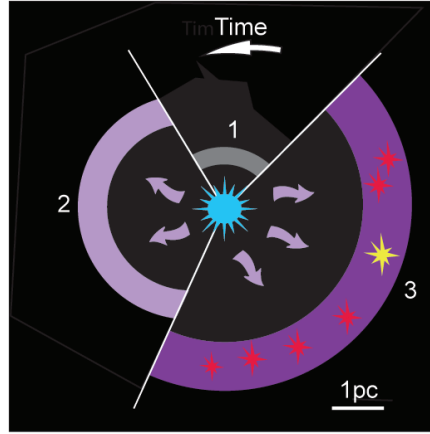
Figure 2. Incorporation of ^{26}Al in a dense shell created by a massive star wind. Phases 1 and 2 correspond to the collection of interstellar gas and injection of ^{26}Al by the wind (arrows). Phase 3 corresponds to the gravitational collapse of the shell and the formation of a new, ^{26}Al-rich star and other stars including the Sun (yellow). The whole process lasts a few Myr (see text).

to be located within a few pc from the nascent solar system (Looney et al., 2006). In N-body simulations of the birth environment of the Sun it is often assumed that the progenitor of this supernova was a star with a mass of $\approx 25\ M_\odot$(see section 6). However, from the cosmochemical side there are some difficulties with this scenario.

3.3. Cosmochemical constraints on the birth environment

It is very unlikely to find a protoplanetary disc or a dense core that close to a SN. Before they explode as SNe, massive stars carve large ionized regions in the ISM (called HII regions) where the gas density is too low and temperature too high for star formation to take place. Observations show that even around a massive star that still needs to evolve for 2 Myr before it becomes a SN, discs and cores are found only several parsecs away (Hartmann, 2005), too far to incorporate ^{60}Fe at the solar abundance. In addition, because SNe ejecta are vastly enriched in ^{60}Fe relative to ^{26}Al and their respective solar abundances (Woosley & Weaver 2007), all models relying on SN injection lead to a ^{26}Al/^{60}Fe ratio far lower than the initial solar ratio, unless specific and ad hoc conditions are adopted (Pan et al., 2012). Finally, the initial abundance of ^{60}Fe has been recently revised downwards by almost two orders of magnitude (Moynier et al., 2011; Tang & Dauphas, 2012). The revised ^{60}Fe abundance is compatible with a **somewhat** enhanced galactic background due to stars born and died in the same molecular cloud as the Sun but in a prior generation (Gounelle et al., 2009).

Because supernovae vastly overproduce ^{60}Fe relative to ^{26}Al, ^{26}Al cannot originate from

a single supernova as first proposed by Cameron & Truran (1977). It also implies ^{26}Al cannot have a background origin because at the molecular cloud scale, SLRs are mainly due to supernovae. In addition, the ^{26}Al distribution in the early solar system seems to have been heterogeneous (Liu et al., 2012a; Larsen et al., 2011), which is incompatible with a global (molecular cloud) scale origin (Young, 2014).

The most likely origin for ^{26}Al is therefore local, i.e. the wind of a single massive star (Arnould et al., 2006). Tatischeff et al. (2010) proposed that a single runaway Wolf-Rayet (WR) star injected ^{26}Al in a shock-induced dense shell. Given the required velocity of the star (20 pc/Myr) and gas ambient density (n $\sim$ 100 cm^{-3}) it is however likely the star will have escaped the molecular cloud well before the star collects enough gas and enters the WR phase during which ^{26}Al is injected. This model suffers from the brevity and therefore the rarity of the WR phase. Gounelle & Meynet (2012) have proposed that ^{26}Al originated in a wind-collected shell around a massive star (Figure 2). In this model, the dense shell collected by the massive star wind is continuously enriched by ^{26}Al brought to the surface of the star by convection promoted by rotation (Meynet et al., 2008). After several Myr, the collected shell reaches densities large enough to make it gravitationally unstable and a new star generation forms in the shell. In this model, the Sun is a second generation star and the massive star having provided ^{26}Al can be seen as its parent star. This mechanism is generic in the sense that this mode of star formation, though not the rule, is relatively common (Hennebelle et al., 2009). This model constraints the astrophysical context of our Sun's formation as it requires that the parent cluster to which belongs the parent star (baptised *Coatlicue*) contained roughly 1200 stars (Gounelle & Meynet, 2012).

In conclusion, though the origin of SLRs is still a complex and debated issue (see Davis et al. 2014 for a more detailed review) it seems that three star formation spatial scales are relevant. SLRs with the longest half-lives originate at the scale of star complexes, while ^{60}Fe ($T_{1/2}$ = 2.6 Myr) originates at the scale of the molecular cloud and ^{26}Al ($T_{1/2}$= 0.72 Myr) at the local massive star wind scale. The distribution of SLRs in the solar system is the record of hierarchical (in termes of spatial and temporal scales) star formation in the ISM.

4. Protoplanetary discs

Another source of potential information about the formation of the solar system are young stars that are currently forming planets from the disc material surrounding them (Safronov, 1969). These discs form as a consequence of angular momentum conservation during the star formation process (e.g. Shu et al., 1987). In the early stages of the star formation process the disc mediates accretion from the parental core to the forming protostar, while at later stages it provides the natural location and material for the planet formation process. The observational study of the properties and evolution of protoplanetary discs is thus a direct probe of the initial conditions for planet formation.

The presence of protoplanetary discs around young stars was originally inferred from the emission in excess to the stellar photosphere at infrared- and submillimetre-wavelengths (eg. Beckwith et al., 1986, 1990). It was very rapidly understood that the excess emission

was likely due to a disc-like distribution of dust located around and heated by the young star at the centre, this interpretation was also consistent with the dynamics of the molecular gas, which could be interpreted as orbiting the star in Keplerian fashion. The inferred sizes (up to few times 100 AU in radius) and masses (up to 10-20% of the central star mass) were also consistent with the expected values for a pre-solar nebula. These ideas were then spectacularly confirmed by the HST silhouette optical absorption images a few years later (O'dell et al., 1993). Following these initial observations, protoplanetary discs around young solar analogues have been extensively studied in nearby star forming regions. The recent review by Williams & Cieza (2011) summarizes most of our current knowledge of the general properties of protoplanetary disc populations in nearby star forming regions.

4.1. Protoplanetary disc lifetimes

The current best estimate of the lifetime of the disc, or the timescale for planetesimal and gas giant formation, is derived from the variation of the fraction of stars, which show infrared excess as a function of the age of the star forming regions (e.g. Hernández et al., 2007), which is also found to be consistent with the variation of the fraction of young stars that show signs of interactions with the inner disc (e.g. Fedele et al., 2010). The fraction of young stars with inner disc is found to drop exponentially with an e-folding time of ~3 Myr. This estimate is uncertain because of a number of possible systematic and environmental effects, e.g. the uncertainties in the age determination of young stars (Bell et al., 2013), or environmental disc dispersal mechanisms in clusters, which may not be applicable to the progenitors of the bulk of the field stellar population (Pfalzner et al., 2014). Nevertheless, it is obvious that if the majority of stars host planetary systems, the formation process has to occur within a few Myr, at least for planet types, which contain significant gaseous envelopes (gas giants, ice giants and low-density super-Earths). In large star forming complexes in the Magellanic Clouds and our own Galaxy, there is controversial evidence for stars with circumstellar discs at relatively old ages (up to and even beyond 30 Myr Beccari et al., 2010; De Marchi et al., 2011). While in nearby regions the few existing candidates have not been confirmed so far (Manara et al., 2013), it is possible that a small but non-negligible fraction of the stellar population born in large complexes reaccrete a disc and possibly have multiple chances of forming planetary systems (Scicluna et al., 2014).

4.2. Protoplanetary disc gas content and chemistry

Young protoplanetary discs are gas rich and most of the raw material available for planet formation is in the form of molecular gas, just like in clouds and cores. Most of this mass is in the observationally elusive form of H_2 and can only be traced, indirectly, through the emission of less abundant species. The molecular gas content, chemistry and emission from protoplanetary discs has been recently reviewed by Dutrey et al. (2014), and we refer to that work for a detailed account. The key feature for constraining the conditions for planet formation is that around young solar analogues most of the disc midplane is at low temperature and the most abundant molecular species (with the obvious exception of H_2) are frozen inside

the ice mantles of grains. In these conditions, the chemistry is likely to be dominated by reactions on ices and may lead to significant production of complex organic and pre-biotic molecules, as observed in laboratory experiments (e.g. Muñoz Caro et al., 2002; Holtom et al., 2005; Islam et al., 2014). While complex organic compounds have been revealed in solar system objects (Glavin et al., 2006; Elsila et al., 2009), the direct detection and abundance measurements in protoplanetary discs is challenging. Nevertheless, in the cold disc midplane cosmic-ray induced desorption of ices may release a small fraction of the complex molecules in the gas phase, a process similar to the one that is thought to occur in cold protostellar cores (Caselli et al., 2012; Jiménez-Serra et al., 2014).

Alternative promising locations to search for these complex compounds are the snowlines‡ of the major molecular species, which could carry in the gas phase complex organic molecules as impurities as part of the sublimation process. The major snowlines that may produce such an effect are the CO snowline at ~20K and the H_2O one at ~150K. The CO snowline is now within grasp of the ALMA observatory in nearby star forming regions (Mathews et al., 2013; Qi et al., 2013), and much work dedicated to the characterisation of this important transition in protoplanetary discs is expected in the coming years. Future instruments may help quantifying gas to dust ratio by combining high spatial and spectral resolution.

4.3. Protoplanetary disc masses and mass distribution

As a consequence of the complexity of the molecular gas chemistry in discs and the difficulty in observing H_2, the most reliable mass estimates for protoplanetary discs still come from the measurements of the thermal dust emission. Most of the disc is optically thin at submm and longer wavelengths. Therefore, the thermal dust emission is directly proportional to the mass, which can be readily estimated from the observed fluxes assuming a dust opacity coefficient and a temperature structure for the disc. The latter is normally computed using a self consistent thermal balance model, for typical accretion rates measured in young pre-main sequence objects the heating from the central star dominates the disc heating and the thermal structure of the dust is usually well constrained by models (see e.g. Dullemond et al., 2007; Bitsch et al., 2014a)§ The disc masses derived with this method are typically between 0.2% and 20% of the mass of the central star, implying that a large fraction of young solar analogues are hosting a disc with a mass well above the minimum mass solar nebula and in principle capable of forming a planetary system similar to our own (e.g. Andrews et al., 2013; Williams & Cieza, 2011).

High angular resolution observations allow to resolve the disc emission and estimate the distribution of matter in the disc. The surface density of solids, traced by the thermal dust emission, are typically found to fall off as r^{-1} with radial distance r until a critical radius and then drop sharply, consistently with an exponential fall off (e.g. Isella et al., 2007; Hughes

‡ The snow, or ice, line is the distance from a central protostar beyond which ice grains can form.
§ The next challenge in modelling discs will be to include simulataneously an advanced radiation transport treatment and the three-dimenisonla dynamics.

et al., 2008; Andrews et al., 2009; Trotta et al., 2013). The observed surface densities of the most massive discs are broadly consistent with the average surface density of our own solar system (Andrews et al. 2009). However, most systems that have a total mass above the minimum mass solar nebula threshold are larger than our own solar system, resulting in a lower surface density. These estimates are not without uncertainties: firstly, the solids are assumed to trace approximately 1% of the total mass (following the estimates of the dust to gas ratio in the interstellar medium), however this number is highly uncertain in discs and also expected to evolve with time and location, as gas and dust evolve following different pathways; secondly, the dust opacity coefficient depend on the composition, size, shape, and porosity of the dust grains (Natta & Testi, 2004; Testi et al., 2014). Measurements of proto planetary disc masses are relatively rare as of today: up-coming ALMA observations may be able to provide a statistical view of the distribution of dust surface densities and possibly also gas surface densities.

4.4. Dust evolution and the first steps of solids growth

As the dust emission is optically thin, multi-wavelength observations at submillimetre wavelength allow us to probe the dust opacity coefficient, which in turn can be a powerful probe of the grain population properties. In a protoplanetary disc, grains are expected to grow and settle onto the midplane (for a recent review, see Testi et al., 2014). As grains grow to sizes of the same order or larger than observing wavelengths, the dust opacity coefficient dependence with wavelength changes from the typical value of the sub-micron size interstellar grains ($\kappa_\nu \sim \nu^{-1.7}$) to a much shallower dependence, approaching $\kappa_\nu \sim const.$ in the limit of a population of grains all much larger than the observing wavelength (Beckwith et al., 1986; Draine, 2006; Natta et al., 2007). This argument has been used to constrain the level of grain growth in protoplanetary discs, finding that in most discs around young stars the dust has grown to pebble-size aggregates (Testi et al., 2001, 2003; Wilner et al., 2005; Ricci et al., 2010).

The observational results can be understood in the framework of global dust evolution models in discs (e.g. Birnstiel et al., 2010), which describe the evolution of dust in the disc environment based on constraints from laboratory measurements of the grain-grain collision outcomes (see e.g. Blum & Wurm, 2008). More specifically, the emerging observational constraints on the dust grain size distribution as a function of disc radius (Guilloteau et al., 2011; Pérez et al., 2012; Trotta et al., 2013) matches the expectations from the evolutionary models (Birnstiel et al., 2012; Laibe, 2014).

This apparent success hides a number of difficulties that still need to be solved, in particular, smooth disc models still predict a radial drift and fragmentation of the large grains that is inconsistent with the observations and require to artificially slow down the radial drift. The planet formation process then requires that additional growth barriers are overcome, a variety of possibility exist, from pressure traps generated by disc instabilities (e.g. Pinilla et al., 2012), localised growth across snowlines (Ros & Johansen, 2013), or the efficient accretion of pebbles onto existing planetary cores (Lambrechts & Johansen, 2014). Some of

these models predict observational signatures that are within reach of the current generation of observing facilities. Indeed the effect of pressure traps induced by planet-disc interaction has been observed in some systems with ALMA (e.g. van der Marel et al., 2013).

An intriguing development in recent years has been the observation by several groups of the possibility of significant dust evolution before the disc stage in prestellar cores and protostars (Chiang et al., 2012; Miotello et al., 2014). If confirmed, these findings would imply a significant revision of our assumptions on the initial conditions for planet formation in protoplanetary discs.

5. Planet growth

5.1. From dust to pebbles

Planets from the gas and dust present in protoplanetary discs. In the first stage of planet formation dust and ice particles collide and stick together to form larger aggregates (Dominik & Tielens, 1997). The aggregates maintain a high porosity during the growth, since collision speeds are initially too low to cause restructuring. Particles obtain increasingly higher collision speeds as they grow in size and their frictional coupling with the gas diminishes (Voelk et al., 1980; Ormel & Cuzzi, 2007), so that particle pairs decouple from the smallest eddies and thus will have different velocity vectors even when at the same location. An additional contribution to the collision speed is the relative radial and azimuthal drift between different-sized particles (Weidenschilling, 1977).

Silicate dust aggregates in the inner protoplanetary disc are compactified by collisions when they reach approximately mm sizes (Zsom et al., 2010). The combination of high collision speeds and low porosity halts growth by direct sticking, since compact particles cannot dissipate enough energy during a collision to allow sticking (Güttler et al., 2010). This is referred to as the *bouncing barrier*. Ice monomers are generally stickier than silicate monomers and this increases their resistance against compactification (Wada et al., 2009). The size of the constituent monomers also plays an important role in determining the collision outcome. Ice aggregates, which consist of very small monomers of 0.1 μm sizes, can stick at up to 50 m/s collision speeds (Wada et al., 2009). It is nevertheless not known whether such small ice monomers are prevalent in protoplanetary discs or whether sublimation and condensation cycles drive ice particles to much larger sizes (Ros & Johansen, 2013).

5.2. From pebbles to planetesimals

The continued growth from mm-sizes faces the formidable *radial drift barrier*. The gas in the protoplanetary disc is slightly pressure supported in the radial direction, since viscous heating and stellar irradiation heat the inner regions more strongly (Bitsch et al., 2014a). This outwards-directed push on the gas causes the gas to orbit slower than the Keplerian speed, by approximately 50 m/s (Weidenschilling, 1977). Solid particles do not sense the pressure difference from front to back (since their material density is much higher than the gas density), so particles would orbit at the Keplerian speed in absence of gas drag. However, the drag from

the slower moving gas drains particles of their angular momentum and causes them to spiral inwards towards the star. In the asteroid belt the radial drift peaks for m-sized particles, which fall towards the star in a few hundred years, to be destroyed at the silicate sublimation line close to the star. The peak of the radial drift occurs for cm-sized particles in the outer protoplanetary disc where the giant planets form.

There are three main ways by which particles can cross the radial drift barrier:

Mass transfer. At collision speeds from 1 to 25 m/s particles can grow by mass transfer. The projectile is destroyed in the collision but leaves up to 50% of its mass attached to the target (Wurm et al., 2005). Particles stuck at the bouncing barrier do not collide at such high speeds. However, artificially injected cm-sized seeds can grow from the sea of bouncing barrier particles through mass transfer (Windmark et al., 2012). The growth rate is nevertheless too low to compete with the radial drift, so formation of planetesimals by direct sticking requires a reduction in the radial drift speed of the particles, e.g. through the presence of a long-lived pressure bump. Such a pressure bump may arise at the inner edge of the dead zone (Lyra et al., 2008; Kretke et al., 2009; Drążkowska et al., 2013) or around the water ice line where the jump in dust density has been proposed to cause a jump in the turbulent viscosity (Kretke & Lin, 2007), although this requires a very steep viscosity transition at the ice line (Bitsch et al., 2014b).

Fluffy particles. Ice aggregates consisting of small monomers acquire very low densities during their growth, down to 10^{-5} g cm^{-3} (Okuzumi et al., 2012). Particle growth is only able to outcompete the radial drift if the particle grows larger than the mean free path of the gas molecules and enters the Stokes drag force regime. Here the friction time is proportional to the particle radius squared; hence decoupling is much more rapid than in the Epstein regime valid for small particles (Johansen et al., 2014). Very fluffy particles are large enough to be in the Stokes regime and can cross the radial drift barrier within 10 AU by growing in size while drifting radially (Okuzumi et al., 2012). Hence this is a way to cross the radial drift barrier, if particles can remain fluffy and avoid compactification and erosion by the gaseous headwind.

Particle concentration. Particles can become strongly concentrated in the turbulent gas, triggering the formation of planetesimals by a gravitational collapse of the overdense regions. Particles concentrate either *passively* or *actively*. For passive concentration the general mechanism is that particles pile up where the gas pressure is high, since any rotating structure in the turbulent gas flow must be in semi-equilibrium between the dominant forces, namely the pressure gradient force and the centrifugal/Coriolis force (Barge & Sommeria 1995). Particles do not sense gas pressure and must therefore move towards the direction of increasing gas pressure. On the smallest scales of the turbulent flow, approximately km under prevalent conditions in the asteroid belt, mm-sized particles pile up between rapidly over-turning eddies (Cuzzi et al., 2001, 2008). The largest scales of the protoplanetary disc are dominated by the Coriolis force, and the turbulence organises into axisymmetric pressure bumps, surrounded by zonal flows (Fromang & Nelson, 2005; Johansen et al., 2009a; Simon et al., 2012), or elongated vortices (Klahr & Bodenheimer, 2003; Lesur & Papaloizou, 2010; Lyra & Klahr, 2011). In the streaming instability scenario the particles actively drive concentration, by piling up in filaments, which locally accelerate the gas towards the Keplerian speed and hence do

not drift radially (Youdin & Goodman, 2005; Johansen & Youdin, 2007; Bai & Stone, 2010b). Strong particle concentration by the streaming instability is triggered at a metallicity slightly higher than solar (Johansen et al., 2009b; Bai & Stone, 2010a). The gravitational collapse of overdense regions leads to the formation of planetesimals of sizes from 100 to 1000 km (Johansen et al., 2007, 2011, 2012; Kato et al., 2012).

The solar system contains remnant planetesimals from the epoch of planet formation, in the asteroid belt and in the Kuiper belt. These populations of planetesimals can be studied to infer constraints on the actual processes that led to planetesimal formation in the solar system. The relative lack of asteroids smaller than 100 km in diameter, compared to a direct extrapolation from the largest sizes, does not agree with the formation of asteroids by hierarchical coagulation in a population of km-sized planetesimals (Morbidelli et al., 2009, but see Weidenschilling (2011) for an alternative view). Asteroids may instead have had birth sizes larger than 100 km, in agreement with gravitational collapse models, while the smaller asteroids that are found in the asteroid belt today are mainly collisional fragments (Bottke et al., 2005). Large birth sizes have also proposed to explain a similar lack of small Kuiper belt objects (Sheppard & Trujillo, 2010).

5.3. *From planetesimals to planets*

Planetesimals are the building blocks of both terrestrial planets and the cores of the giant planets. In the *core accretion* scenario giant planets form as gas from the protoplanetary disc collapses onto a core that has grown to approximately 10 Earth masses by accumulation of planetesimals (Mizuno, 1980; Pollack et al., 1996). In this picture, the ice giants Uranus and Neptune only manage to attract a few Earth masses of gas before the gaseous protoplanetary disc dissipates after a few million years. Core accretion by planetesimals is nevertheless very slow because the number density of planetesimals is low in the region where the giant planets form. An enhancement of 4-6 over the Minimum Mass Solar Nebula is needed to form Jupiter and Saturn within 10 million years in the classical core accretion scenario (Pollack et al., 1996).

Core accretion timescales can be decreased when accreting planetesimal *fragments*. Small fragments have their scale heights damped by gas drag and hence the growing core can accrete a much larger fraction of the solid material (Goldreich et al., 2004; Rafikov, 2004). However, global disc simulations show that a large fraction of the slowly drifting fragments are trapped in resonances with the cores (Levison et al., 2010). The formation of a system of giant planets is further complicated by the excitation of planetesimal eccentricities and inclinations when scattered by the growing cores. This leads to a slow oligarchic growth phase with growth rates that are too low to form cores within the life-time of the protoplanetary disc (Levison et al., 2010).

Pebbles left over from the planetesimal formation process can be accreted very efficiently by the growing cores (Johansen & Lacerda, 2010; Ormel & Klahr, 2010; Lambrechts & Johansen, 2012; Morbidelli & Nesvorny, 2012). The Hill sphere of the core denotes the radial distance over which an incoming particle on a faster (interior) or slower (exterior) orbit is
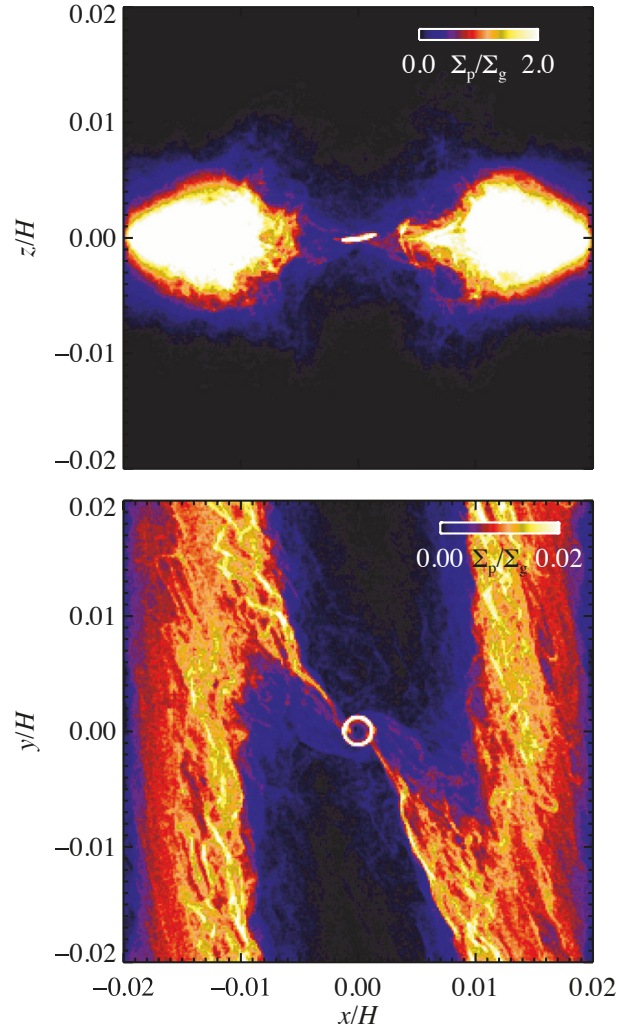
Figure 3. Accretion of pebbles onto a 1000-km-scale protoplanet. The simulation box corotates with the protoplanetary disc at an arbitrary distance from the star. The top plot shows the column density of cm-sized pebbles in the radial-vertical plane, while the bottom plot shows the column density in the radial-azimuthal plane. Two streamers of material enter the Hill sphere, which is approximately 0.007 times the gas scale-height H for the considered protoplanet mass, and feed a particle accretion disc orbiting the protoplanet. Figure adapted from Johansen & Lacerda (2010).

scattered gravitationally by the core. The core only extends a small fraction of its Hill radius (0.1% at 5 AU, 0.01% at 50 AU). Gravitational focussing of the incoming planetesimals makes the accretion radius much larger than the physical radius, but planetesimals are still only accreted from about 3% of the Hill radius at 5 AU. Pebbles of mm-cm sizes experience strong drag during the gravitational scattering and lose enough energy to be gravitationally bound to the core, for any impact parameter up to approximately the Hill radius (see Figure 3). This leads to very high accretion rates, about 1,000 times faster than classical core accretion at 5 AU and 10,000 times faster at 50 AU. Such high growth rates are needed to explain the formation of gas giants observed in wide orbits around some young stars (e.g. HR8799, Marois et al.,

2008, 2010) assuming they are not formed from other means (like gravitational instability). As detailed in section 4.4, protoplanetary discs observed at mm- and cm-wavelengths show signs of large populations of mm-cm-sized pebbles, which can boost planet formation (Testi et al., 2003, 2014).

Many of the young stars surrounded by discs are part of a cluster of stars, indeed it seems that most stars are born in a clustered environment (Lada & Lada 2003). In the next section we will discuss the possible birth environment of the Sun. In particular we consider whether we can constrain the properties of the birth cluster, indeed its possible identity, and whether we can identify solar siblings, i.e. the stars that were born from the same molecular cloud as the Sun (see for example, Portegies Zwart, 2009; Adams, 2010; Pfalzner, 2013).

6. Formation within stellar clusters

6.1. Evidence suggesting the Sun formed in a stellar cluster

Analysis of the isotopic abundances of meteorites reveal that they contain the decay products of the radioactive isotopes ^{26}Al and ^{60}Fe, which have half lives of 0.7 Myr and 2.6 Myr (Lee et al., 1976). As mentioned in section 3 the most likely source of these isotopes are supernovae explosions (e.g. Chevalier, 2000). How many is still a matter of debate. Given the observed distribution of stellar masses of newly-formed stars follows a power law favouring less-mass stars ($dN/dm \propto m^{-2.35}$ - Salpeter, 1955) one would need a fairly large group of stars reasonably close to the forming Sun to explain the observed abundancies.

There are other indications that the Sun once was part of a fairly dense and therefore large stellar cluster. First, the fairly abrupt cut-off in the mass distribution at 30-50AU, which is usually not observed in protoplanetary discs, but could be caused by a fly-by during the protoplanetary disc phase. Second, the trans-Neptunian objects Sedna and 2012VP$_{113}$ (Morbidelli & Levison 2004, Kenyon & Bromley 2004, Brasser et al. 2006, Trujillo & Sheppard 2014) with their high excentricities are another property that could be explained by an encounter during the planet forming phase. Calculations of encounter probabilities in clusters suggest that the Sun was formed in a stellar cluster containing 2000 to 10000 stars (Portegies Zwart 2009). Further evidence for the sun having been in a cluster, comes from the measured tilt of the sun's rotation, one suggestion being that the protoplanetary disc was titled by a star-disc interaction (Heller 1993; Thies et al. 2005).

6.2. Encounters and other processes within stellar clusters

Stellar clusters are potentially dangerous environments for planetary systems. Close encounters between stars are relatively frequent in such crowded places. The timescale for a particular star to have another star pass within some distance $R_{\min}$ can be approximated by (Binney & Tremaine, 2008)

$$\tau_{enc} \simeq 3.3 \times 10^7 \mathrm{yr} \left(\frac{100 \ \mathrm{pc}^{-3}}{n} \right) \left(\frac{v_\infty}{1 \ \mathrm{km/s}} \right) \left(\frac{10^3 \ \mathrm{AU}}{r_{min}} \right) \left(\frac{\mathrm{M}_\odot}{M} \right) \tag{1}$$

One can distinguish between different phases during which such an encounter could happen: (i) the early phase when the star is surrounded by an accretion disc (first few Myr), (ii) the planet growth phase, and (up to 100 Myr), and (iii) after the solar system was fully formed (up to now). Close encounters occurring whilst stars still possess protoplanetary discs could lead to their truncation (Kobayashi & Ida, 2001; Forgan & Rice, 2009; Breslau et al., 2014; Rosotti et al., 2014). In addition, illumination by massive stars may lead to the early evaporation of protoplanetary discs around young stars (Armitage, 2000). Thus, clusters may inhibit the planet formation process.

Planetary systems, once formed, are also affected by other stars within clusters. Fly-by encounters with other stars may perturb otherwise stable planetary systems (e.g. Malmberg et al., 2007b, 2011) Changes in planetary orbits within a system can lead to the growth in eccentricities until orbits cross. Scattering can then lead to the ejection of planets leaving those remaining on more bound and eccentric orbits. For lower-mass planets on tighter orbits, orbit crossing tends to lead to collisions between planets (e.g. Davies et al., 2013). Alternatively, stars hosting planetary systems may exchange into (wide) binaries. The stellar companion may then perturb planets' orbits via the Kozai-Lidov mechanism, where planets' orbits periodically pass through phases of high eccentricity. Planetary orbits may then cross leading to scattering or collisions (e.g. Malmberg et al., 2007a; Davies et al., 2013). In the early phases the probability of encounters are highest, as afterwards clusters expand and therefore the encounter likelihood decreases.

6.3. Placing the solar system inside a stellar cluster

We have seen above how the measured isotopic abundances in meteorites are well explained by the enrichment of the protosolar-system material from a nearby supernova formed from a relatively massive star or from a combination of supernovae and a massive ^{26}Al-producing star. The rarity of such objects in turn led us to argue that the solar system likely formed within a stellar cluster containing at least 2000 stars. As just discussed, stellar clusters are hazardous environments. The rate of destructive close stellar encounters tends to increase with increasing cluster mass (see Eq. 1). Therefore, there is an optimum stellar cluster containing around a few thousand stars where pollution from supernovae is at least possible whilst at the same time a reasonable fraction of planetary systems may survive unperturbed (Adams & Laughlin, 2001). One can perform N-body simulations of stellar clusters containing one 25 $M_\odot$ star to determine the number of solar-like stars, which are 0.1 - 0.3 pc from the 25 $M_\odot$ star when it explodes as a supernova. One can then follow the subsequent trajectories of these polluted stars within the cluster to determine the fraction of them, which avoid both perturbing fly-by encounters and exchange encounters into binaries. Such numerical studies of clusters containing 2100 stars (including one 25 $M_\odot$ star) reveal that some 25 percent of clusters contain enriched, unperturbed solar-like stars (i.e. G-dwarfs), and usually only one or two per cluster out of a total of 96 G-dwarfs (Parker et al., 2014). Therefore, roughly one percent of G-dwarfs from such clusters are enriched whilst being unperturbed.
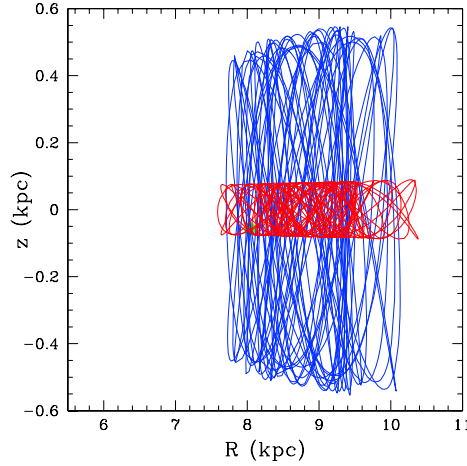
Figure 4. The current orbits of the Sun (red line) and the open cluster M 67 (blue line) in cylindrical coordinates where *R* is the cylindrical radius from the Galactic centre and *z* is the distance from the Galactic plane (Figure 7 of Pichardo et al., 2012, reproduced with permission of the AAS).

6.4. M 67 as a possible host cluster

If the Sun was indeed born in an open cluster, it is rather natural to ask whether this cluster is still around today, and if so, whether we can identify it. There have been a number of observations of star clusters of different ages dedicated to find planets in them (Meibom et al. 2013, and references therein). However, planet detection in clusters provides some added difficulties, for example, even nearby clusters are often more distant than the field stars one finds usually planets around), thus the frequency of planets in cluster environments compared to that in the field is still an open question. However, probably most clusters in the solar neighbourhood loose a considerable fraction (> 70%) of their stars (Pfalzner & Kaczmarek 2013). Measuring detailed abundance patterns in stellar atmospheres through high-resolution spectroscopy offers us the hope of identifying other stars, which originate from the same gas cloud as the Sun (e.g. Portegies Zwart, 2009; Portegies Zwart et al., 2010). Even if the cluster has long since dissolved, stars from it will still share similar orbits whose properties could be measured astrometrically (e.g. Brown et al., 2010).

The open cluster M 67 is one candidate which we will consider here, though there must have been a number of cluster produced in the Milky way having similar ages and galactocentric radii. M 67 has an age. of about 3.5–4.8 Gyr (Yadav et al., 2008) and the stars within it also have a composition similar to the Sun. Önehag et al. (2011) have identified one star in the cluster, which is a better match to our Sun than most solar-like stars in the solar neighbourhood. The analysis of 13 additional stars in M 67 confirm that the abundances of the Sun and M 67 are similar (Önehag et al., 2014).

However, as pointed out by Pichardo et al. (2012) the current orbits of M 67 and the Sun are very different, as shown in Fig. 4, where we plot their current orbits in cylindrical coordinates (figure 7 from Pichardo et al., 2012). The radial distance from the galactic centre, R, for the Sun and M67 are similar. Earlier mention of abundance enhancements in the Sun compared to its distance from the Galactic centre (Holmberg et al., 2009) would indicate that the Sun experienced a radial migration of 0.8–4.1 kpc (Minchev et al., 2013). In that case M 67 should also have migrated over the same distance. Possibly, the migration happened while the Sun was still a member of its birth cluster. Extensive numerical analysis of the orbit of the Sun in the Galactic potential however indicates that this radial migration in the current Galactic potential would be negligible (Martínez-Barbosa et al., 2014).

One can see from Fig. 4 that the orbit of M 67 takes the cluster significantly further out of the galactic plane to much larger values of z than is experienced by the Sun. If one assumes that M 67 has always had its current orbit and that the Sun was ejected from M 67, this would imply that the Sun received a significant kick in order to leave it on its current orbit, residing in the plane of the galaxy (Pichardo et al., 2012). The point here is that it is not possible to impart such a large kick whilst keeping the solar system intact.

A possible solution to this problem has been suggested in Gustafsson et al. (2014). The key idea is that the orbit of M 67 has changed over time. The orbit could originally have been more in the galactic plane (i.e. with lower maximum values of z) allowing the Sun to escape from it with a relatively low velocity. Scattering off giant molecular clouds (GMCs) could then leave the cluster on the orbit we see today. Simulations of scattering due to GMCs show that it is possible to put M 67 on its current orbit beginning with an orbit similar to the Sun's (Gustafsson et al., 2014). In that case the Sun must have left M 67 before the scattering event with a GMC took place.

7. The Kuiper Belt and the Late Heavy Bombardment

7.1. The Kuiper Belt

Beyond Neptune lies a reservoir of remnant icy planetesimals from the formation of the solar system analogous to the main asteroid belt between Mars and Jupiter. Known as the Kuiper belt, this distant population displays an intricate orbital structure that has inspired and constrained a number of ideas on the early evolution of our planetary system. The high abundance of Kuiper belt objects (KBOs) in mean-motion resonances with planet Neptune led to the idea that the ice giant has migrated through the original disc of planetesimals, sweeping a significant fraction into stable resonant orbits (Malhotra, 1995). The superposition of dynamically hot (high inclination and eccentricity) and cold (low inclination and nearly circular) orbits suggests that while some KBOs have been scattered onto their current orbits (Gomes, 2003), likely by the outer planets, others have formed in-situ and remained unperturbed (Batygin et al., 2011). An alternative explanantion is provided by an encountering star that scattered the Kuiper belt (Ida et al. 2000). The current morphology of the scattered Kuiper belt could only be reproduced if the mass of the encountering star M had an impact

parameter of $b = 170 + 45(M/M_\odot - 0.5)$ AU (Punzo et al. 2014). However, such an encounter would like scatter the entire Kuiperbelt. In addition, cooling off part of the hot population to re-populate the cold population would require some 1000 Pluto-mass objects, which are not observed.

7.2. Early Dynamical Evolution

The need to explain the dynamical structure of the Kuiper belt and to reconcile the orbits of the giant planets with the discovery of hot-Jupiters were main drivers in the evolution of planet migration theories. In the solar system, the current paradigm considers that the giant planets emerged from the protoplanetary disc in a more compact, near-resonant configuration, all within 15 AU from the Sun (Batygin & Brown, 2010). Angular momentum exchanges with the surrounding disc of planetesimals led to the outward migration of Neptune, Uranus, and Saturn, as they scattered small bodies inwards, while Jupiter, sufficiently massive to eject planetesimals from the solar system, migrated predominantly towards the Sun (Fernandez & Ip, 1984; Hahn & Malhotra, 1999). The diverging migrations of Jupiter and Saturn eventually resulted in a mutual resonance crossing and triggered a dynamical instability throughout the solar system, which impulsively expanded the orbits of Uranus and Neptune to near their current locations and violently scattered the planetesimal disc (Tsiganis et al., 2005). The Late Heavy Bombardment was also likely caused by this instability event (Gomes et al., 2005).

7.3. The Late Heavy Bombardment

Geochronological studies of the lunar rocks returned by the Apollo missions yielded the surprising result that all large multi-ring basins on the Earth's moon – they are also called Mare: Orientale, Crisium, Imbrium, Nectaris, Humorum, Serenitatis – originated by giant impacts in an extremely confined time interval between 4.0 and 3.7 Gyr ago (Tera et al., 1974; Turner, 1977; Jessberger et al., 1974). This process is called the Lunar (or Late) Heavy Bombardment (LHB), as it was completed only 800 Myr after solar system formation. It requires that long after final formation of the terrestrial planets, there was an increased flux of small bodies (up to about 100 km in size) in the inner solar system 3.8 Gyr ago. Possible evidence of the LHB is also inferred from HED meteorites (Bogard, 1995; Kunz et al., 1995; Bogard & Garrison, 2003), which are inferred to come from Vesta, and Martian meteorites like ALHA84001 (Ash et al., 1996; Turner et al., 1997), although this is not undisputed (Bogard & Garrison, 1999).

Two general scenarios appear plausible for the early solar system impact history:

i) The LHB was the final phase of terrestrial planet accretion – this requires that the small body flux must have been considerably higher before (implying somewhat unrealistic total mass estimations of initial small body populations), and that the record of earlier impacts must have been erased by the late impact phase 3.8 Gyr ago.

ii) The LHB was an episodic spike of the influx of asteroidal or cometary bodies, caused by dynamical excitation of small body populations in the asteroid or Kuiper belts. As general explanation for the dynamical excitation, planetary migration processes are promising

candidates, in particular the aforementioned resonance crossing of Jupiter and Saturn (Gomes et al., 2005; Tsiganis et al., 2005), i.e. in more general terms, the giant planet instability (Morbidelli et al., 2007, Levison et al., 2011). Advanced models consider a more prolonged bombardment history induced by planet migration processes (Morbidelli et al. 2012).

However, there is increasing evidence that before the time of the LHB 3.8 Gyr ago, there were other episodic times of increased impact rates on the Earth-moon system, registered by, e.g. Ar-Ar and zircon chronology (Fernandes et al., 2013; Nemchin et al., 2008), and also by other meteorite parent bodies, e.g. 4.2 Gyr impact events affecting the LL chondrite parent body (Trieloff et al., 1989, 1994; Dixon et al., 2004). It was suggested (Trieloff, 2014) to consider close stellar encounters as a possible reason for repeated episodic dynamical excitation. However, there is increasing evidence that before the time of the LHB 3.8 Gyr ago, there were other episodic times of increased impact rates on the Earth-moon system, with concomitant impact episodes on other inner solar system bodies. For example, both Ar-Ar and zircon chronology (Fernandes et al. 2013, Nemchin et al. 2008) evidence an increased impact cratering rate 4.2 Ga ago, which was also experienced by the LL chondrite parent body (Trieloff et al. 1989, 1994, Dixon et al. 2004). Although the chronological data base has still to be improved, age clustering can only hardly be reconciled with stochastical bias effects, as multiple celestial bodies were affected. As giant planet instabilities can only once trigger bombardments, it was suggested (Trieloff 2014) to consider close stellar encounters as a possible reason for repeated episodic dynamical excitation. However, the corresponding dynamical scenarios are only poorly explored.

7.4. Decoding KBO Diversity

KBOs possess the most diverse surfaces of any small body population in the solar system (Luu & Jewitt, 1996; Jewitt & Luu, 1998). This is puzzling, given the low and slowly varying temperatures in the Kuiper belt region. The migration-driven instability event described above offers a plausible solution to this problem by allowing planetesimals formed in the ~10 to 30 AU region to be scattered to the current Kuiper belt. However, the stochastic character of this process complicates the mapping of current KBO surface properties to their formation location. A recent survey of KBOs and Centaurs using *Herschel* (Müller et al., 2009) has built on an earlier *Spitzer* survey (Stansberry et al., 2008) to produce the largest sample of albedos and sizes for this type of object (Table 1). These data reveal that KBOs are also extremely diverse in reflectivity, with albedos spanning more than an order of magnitude from about 0.03 to 0.40. An interesting trend emerges when combining the KBO colour and albedo data (Lacerda et al., 2014): an albedo-colour plot (Figure 5) shows that KBOs fall into two main groups: a broad bright-red (BR) cluster, centred around albedo ~0.15 and colour spectral slope ~30% and a more compact dark-neutral (DN) clump near albedo ~0.05 and colour slope ~10%. Importantly, KBOs in dynamical classes believed to originate beyond Neptune occupy only the bright-red group, while KBOs that may have been scattered out to the Kuiper belt from nearer the Sun are found in both the bright-red and the dark-neutral groups. This result hints at a compositional gradient that was present in the planetesimal disc
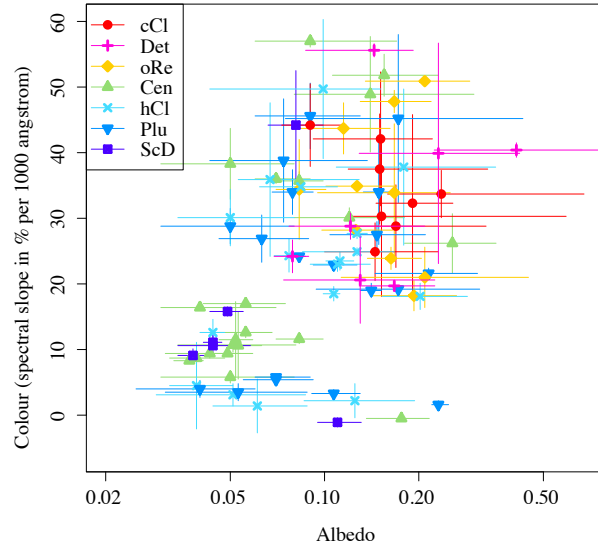
Figure 5. Albedo and colour distribution of intermediate-sized KBOs in the Herschel sample. Selected dynamical classes are plotted: Cen=Centaurs, Plu=Plutinos, ScD=Scattered Disc, hCl=Hot Classicals, Det=Detached, cCl=Cold Classicals, oRe=Outer Resonants (beyond the classical belt). For a description of these dynamical classes see Gladman et al. (2008).

Table 1. Summary of the KBO/Centaur Herschel Sample Properties. Columns are 1) Dynamical class (Gladman et al., 2008), 2) median albedo and central 68% interval, 3) mean spectral slope in %/(1000 Å) and standard deviation. Statistics includes measurement uncertainties by bootstrap resampling and excludes dwarf planets and Haumea-type KBOs. 4) Dominant surface types (BR=bright-red, DN=dark-neutral) present in class (see caption for Figure 5)

Dynamical class	Albedo	Colour	Surface Types
Scattered Disc	$0.05^{+0.04}_{-0.01}$	16.3 ± 12.6	DN, BR
Centaurs	$0.06^{+0.07}_{-0.02}$	21.5 ± 16.5	DN, BR
Hot Classicals	$0.08^{+0.05}_{-0.04}$	22.8 ± 15.6	DN, BR
Plutinos	$0.09^{+0.07}_{-0.04}$	20.1 ± 15.4	DN, BR
Outer Resonants	$0.13^{+0.09}_{-0.05}$	31.6 ± 12.8	BR
Cold Classicals	$0.15^{+0.08}_{-0.06}$	33.2 ± 10.3	BR
Detached KBOs	$0.17^{+0.20}_{-0.09}$	33.2 ± 14.6	BR

prior to the planetary instability event.

8. Long-Term Evolution

Planetary system development is often considered in the context of *dynamical stability*, or the ability of a planet, moon, or asteroid to adhere to its regular motion – i.e. approximately retain its original orbit – over time. Past or future instability can help constrain and explain observations and place our solar system today into context (Davies et al., 2013). In this section, we ask, are planetary systems - and in particular the solar system - stable as their host
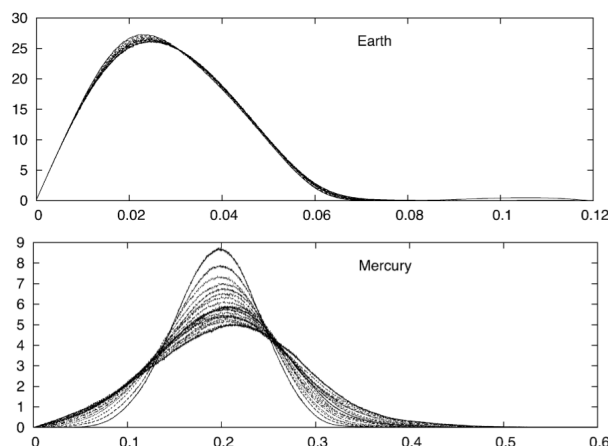
Figure 6. From Figure 9 of Laskar (2008): Normalised density functions for the eccentricities of Earth and Mercury. On each plot the 19 curves represent intervals of 250 Myr. Each curve is based on 1001 solutions with very close initial conditions. The variation of these curves reflects the chaotic diffusion of the solutions. Mercury's eccentricity is clearly shown on average to increase with time, whereas the Earth's eccentricity remains relatively constant.

stars evolve?

8.1. Long-Term Evolution of the Solar System

The future orbital evolution of the solar system, like all other planetary systems, cannot be determined to infinite precision. Instead, we obtain likelihoods for particular futures through suites of numerical simulations. Qualitatively, the evolutionary behaviour can be split into two parts depending on the state of the Sun: (i) the main sequence and (ii) post-main-sequence phases of Solar evolution.

The Sun will exist in its present state for about a further 6 Gyr before turning off the main sequence. During these 6 Gyr, the eight planets will technically evolve chaotically (Sussman & Wisdom, 1988; Laskar, 1989) but realistically are very likely to avoid dynamical instability. In fact, through a suite of simulations, Laskar (2008) determined that the inner four planets have a 98%-99% chance of surviving and not having planetary orbits cross; 100% of all his simulations yielded survival of the outer four planets. Figure 6 shows how the eccentricity of the Earth and Mercury evolve over this timescale. Earth's eccentricity remains nearly constant. Mercury's eccentricity gradually increases, but rarely becomes large enough for its orbit to cross that of Venus.

After the Sun leaves the main sequence, it will simultaneously shed about half of its mass while becoming a red giant star that is nearly 1 AU in radius. The increase in radius can more easily allow the Sun to tidally capture objects encountered by the Solar envelope (Villaver et al., 2014), whereas the mass loss will push out and potentially warp the orbits of surviving bodies (Hadjidemetriou, 1963).

The result on the inner three planets will be dramatic, and on the outer five less so. Mercury and Venus will be swallowed and Earth will suffer an uncertain fate. Our home

planet will lie on the cusp of being tidally drawn into the Sun (Schröder & Connon Smith, 2008). Mars's orbit will simply expand. All 4 outer planets will also survive and expand their orbits such that the ratios of their mutual separations will remain unchanged (Duncan & Lissauer, 1998). Beyond Neptune and the Kuiper belt, the Sun's mass loss will trigger instability in the Oort cloud, allowing for objects beyond $10^3 - 10^4$ AU to escape the solar system (Veras & Wyatt, 2012).

8.2. Long-Term Evolution of Other Planetary Systems

Observational data for extrasolar planets are significantly less accurate and precise than those for the solar system planets (Perryman, 2011). Consequently, the future of exoplanetary systems is not as well constrained. However, every exoplanetary system so far discovered contains fewer planets than the solar system, simplifying the analysis.

The majority of known planetary systems contain either two or three planets (www.exoplanets.org), motivating study of these two cases in detail. During the main sequence evolution of the host star two planets will never cross orbits if they are sufficiently far away from each other to be *Hill stable* || (Gladman, 1993). A Hill stable system could potentially become *Lagrange unstable* if the inner planet collides with the star or the outer planet escapes the system (Barnes & Greenberg, 2006). Empirical and analytical estimates for these stability boundaries, even when scaled down in mass to the test particle limit, show good agreement with numerical simulations of the long-term evolution (Wisdom, 1980; Mustill & Wyatt, 2012; Deck et al., 2013; Giuppone et al., 2013; Veras & Mustill, 2013).

Three-planet systems do not appear to admit analytical stability boundaries, and therefore investigations of these systems require a numerical approach. These studies have yielded portraits of instability times as a function of initial separation, as well as empirical estimates for these times (Chambers et al., 1996; Marzari & Weidenschilling, 2002; Chatterjee et al., 2008). These instabilities can occur any time during the main sequence evolution, and fundamentally change the resulting dynamical architecture, perhaps leading to the establishment of a population of hot Jupiters and eccentric planets (Beaugé & Nesvorný, 2012). The study of systems with a higher number of exoplanets produce a similarly-wide variety of outcomes to the three-planet case (Smith & Lissauer, 2009).

We know that planetary systems do survive the giant branch phases of stellar evolution based on abundant evidence of atmospheric metal pollution in white dwarfs (WDs) (Zuckerman et al., 2010; Koester et al., 2014); WDs, which are the size of the Earth but with the mass of the Sun, represent the end-product of stellar evolution. In over 35 systems, WD atmospheric metal pollution is accompanied by compact accretion discs of gas and/or dust (Gänsicke et al., 2006; Farihi et al., 2009). Although the precise origin of the pollution and discs have yet to be identified, they must arise from currently dynamically active planetary system remnants.

|| The concepts of Hill and Lagrange stability are applicable to 3-body systems (2-planet systems) only. In a Hill stable system, the orbits of both planets can never cross. A Lagrange stable system is Hill stable and also does not allow the outer planet to escape the system nor the inner planet to crash into the star.
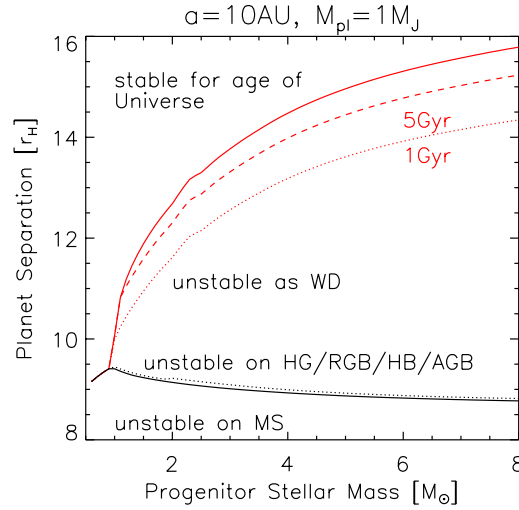
Figure 7. Fig. 1 of Mustill, Veras & Villaver (2014): Approximate stability behaviour of three-planet systems as a function of stellar mass and separation on the main sequence (MS). The quantity r_H on the y-axis represents the single-planet Hill radius. The planet mass and the innermost semi-major axis are fixed at 1 M_J and 10 AU, respectively. Systems below the black solid line will be unstable on the MS. Systems in the tiny strip between the black solid and the black dotted lines will become unstable at some point between the end of the MS and the end of the asymptotic giant branch (AGB). Systems below the red solid line will be unstable during the WD phase, assuming that the star formed at the big bang; systems above this line must be stable for the age of the Universe. The red dotted and dashed lines show the stability boundaries for WD cooling ages of 1 and 5 Gyr. This plot demonstrates that after the star has become a white dwarf, many more systems can become unstable.

During giant branch mass loss, the dynamical stability limits of a multi-body system are changed (Debes & Sigurdsson, 2002). Consequently, two-planet systems, which remained stable throughout the entire main sequence may become unstable either during the giant branch phase, or the WD phase (Veras et al., 2013). For three-planet systems, the situation becomes more complex, allowing for multiple instabilities to occur during different phases of stellar evolution (Mustill et al., 2014). See Figure 7 for a phase portrait of stability limits through all phases of stellar evolution for three-planet systems. Planets residing close to the giant star will tidally interact in a complex way depending on the pulsations of the giant (Mustill & Villaver, 2012).

A likely progenitor of the WD discs are exo-asteroids. Although unobservable during main sequence and giant branch phases, their evolution through these epochs will crucially determine their placement in WD systems. The effect of mass loss on a single planet and single exo-asteroid belt has been considered in the context of an exo-Kuiper belt at about 30 AU (Bonsor et al., 2011) and an exo-asteroid belt at about 5 AU (Debes et al., 2012; Frewen & Hansen, 2014).

9. Summary

Combining the evidence from these different sources for the early history of the solar system the following picture emerges:

The geochemical and isotopic inventory of meteorites provides a unique chronological record of early solar system evolution. It took less than one million years after condensation of the first solid matter to form the first generation of planetesimals. These planetesimals underwent internal heating between 1 and 4 million years after the solar system formation, largely caused by ^{26}Al decay, triggering their differentiation into metal core and silicate mantle. The parent asteroids of undifferentiated chondritic meteorites formed 1-2 million years later, and therefore these bodies did not differentiate. Formation of the larger terrestrial planets in the inner solar system likely occurred via collisions of smaller asteroidal bodies. The timescales involved in planetary growth are of the order tens of millions of years, with Mars being a possible exception due to gravitational interaction with nearby Jupiter. There is growing evidence that the volatile element inventory of the inner solar system was added later, i.e. during the last stages of planetary growth.

The presence of the remnants of short-lived radioactive nuclei in meteorites was for a long time interpreted as evidence for the formation of the Sun in a large star cluster. It was usually assumed that the different radioactive nuclei were formed in one single event in a supernova explosion. However, there now exist arguments to support that a sequence of events took place. Here the SLRs with the longest half-lives originate from star complexes, while ^{60}Fe ($T_{1/2} = 2.6$ Myr) originates from a molecular cloud and ^{26}Al ($T_{1/2} = 0.72$ Myr) from the wind of a local massive star. In this picture the distribution of SLRs in the solar system is the result of sequential star formation in the ISM.

The observation of young disc-surrounded stars also imposes constraints on the timescale of planet formation. The disc fractions in star clusters strongly indicate that most stars dissipate their discs within 2-3 Myr which would favour rapid planet formation - at least for the gas giants. However, recent works argue in favour of longer disc dissipation times, of the order of 5-10 Myr. Here a comparison with the meteorite record could possibly bring clarification in the future.

Comparing the typical masses of the discs around young stars it is found a large fraction of young solar analogues are hosting a disc with a mass well above the minimum mass solar nebula and in principle are capable of forming a planetary system similar to our own. For the most massive of these discs the observed surface densities distribution of the disc mass is roughly consistent with the average surface density of our own solar system. However, most systems are larger than our own solar system, resulting in a lower surface density. It is currently unclear whether this difference is real or due to the large uncertainties in the observations.

The formation of planets from dust and ice particles likely proceeds in the initial stages by sticking collision, the so-formed porose aggregates eventually compactify. The continued growth from mm-sized particles faces the the formidable bouncing and radial drift barrier. Planetesimals form despite these difficult circumstances, likely by a combination of particle

sticking and gravitational collapse of regions overdense in pebble-sized particles. The various mechanisms which allow particles to avoid this process have been suggested. Future studies of the properties of the remnant planetesimals in the asteroid belt and in the Kuiper belt will be crucial to shed light on this open issue. In addition, studying protoplanetary discs will help to understand this phase of planet formation better, as populations of mm-cm sized pebbles have been detected in discs around young stars.

It is presently unclear to what degree nearby others stars influence the formation of planetary systems. From the SLR abundances and the size of the solar system it can be concluded that the birth cluster of the Sun contained at least 2000 stars. Measuring detailed abundance patterns several groups have recently started the search for other stars that originate from the same gas cloud as the Sun. There are currently some candidate siblings, however further studies are required to confirm those results.

The orbital structure of the Kuiper belt and the cratering record on the Moon are evidence for a dynamically active early solar system. Planetary migration and resonance-driven instabilities have acted on the planetesimal disc to enhance impact rates onto the inner solar system, to boost the mixing of populations formed at different distances from the Sun, and to sculpt the dynamics of the main planetesimal reservoirs. On the other hand, external forces from close stellar encounters within the Suns parental cluster could have been the cause of episodic dynamical excitations of minor body populations and impact rates. The current challenge for understanding the origin of the solar system (and other planetary systems) is to seek clues that allow us to see past these dynamical events, to the time when the first planetesimals began to form.

What will happen to the solar system in the future? After the Sun leaves the main sequence Mercury and Venus will be swallowed and Earth will suffer an uncertain fate as it will lie on the cusp of being tidally drawn into the Sun. Mars and the 4 outer planets will also survive and expand their orbits.

In summary, in recent years we have seen many new insights into the formation of the solar system. However, there are still a considerable number of open questions where different competing theories exist. So far the different fields contributing in the investigations to the origin of the solar system have generally worked fairly orthogonally. However, it would be timely to start combining these seperate efforts, using them to build a more complete pictures. Progress can be expected in determining the actual chronology of events.

Acknowledgements

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