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Planetary Formation: Lessons Learned from the Solar System and the Extrasolar Planets

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Our understanding of planetary formation as derived from the Solar System, for decades the only example of a planetary system we knew, has been challenged over the last twenty years by the rich diversity of discovered extrasolar planets. The Solar System, however, still represent a unique source of detailed information on the processes shaping the formation and subsequent evolution of planets, both individually and as a whole. Over the last ten years, in particular, the study of the geochronology of meteorites supplied new and highly detailed data on the relative timescales of formation and geophysical evolution of the different classes of planetary bodies. At the same time, new theoretical works on the formation and early dynamical evolution of the giant planets helped bridging the gap between the story told by the Solar System and that coming from the extrasolar planets. This talk will provide a review of these recent advancements and discuss how they affected our understanding of the earliest and more mysterious phases of the life of planetary systems.

Keywords: Planetary Formation - Solar System - Extrasolar Planets - Meteorites - Planetesimals - Giant Planets - Migration

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1. Introduction

For decades the Solar System has been the only planetary system that we knew of and that we could study in detail: as a consequence, our understanding of planetary formation was shaped along the line of its characteristics. The expected outcome of the planetary formation process were well-spaced and dynamically stable planetary systems, with the terrestrial planets inhabiting the inner orbital regions and the giant planets populating the outer ones. The division between the inner and outer regions of the planetary systems coincided with the water ice condensation line, outside of which water would crystallize enhancing the amount of solid material available to form of the cores of the giant planets. In this classical view, planetary migration due to planetary encounters or exchange of angular momentum with the circumstellar disc was generally expected to be globally limited and stochastic.

The discovery of extrasolar planets changed this framework: in particular, the discovery of giant planets orbiting their parent stars with semimajor axes of the order of tenths or hundredths of astronomical units (au) and of giant planets with orbits characterized by far larger eccentricities than those observed in the Solar System (see Fig. 1) showed that planetary encounters and migration played a much more significant role in shaping the final structure of a planetary system than previously thought. All this put to question whether our Solar System is indeed representative of a typical planetary system and whether models and scenarios developed to explain its formation can be considered general in a galactic context. What extrasolar planets can offer in terms of statistics of the possible outcomes of the planetary formation process, however, they lack in terms of details. Aside for a few cases, the only information we possess on extrasolar planets is dynamical, i.e. that supplied by their orbits. Even in the few cases for which we possess some compositional information, data are limited and affected by large uncertainties.

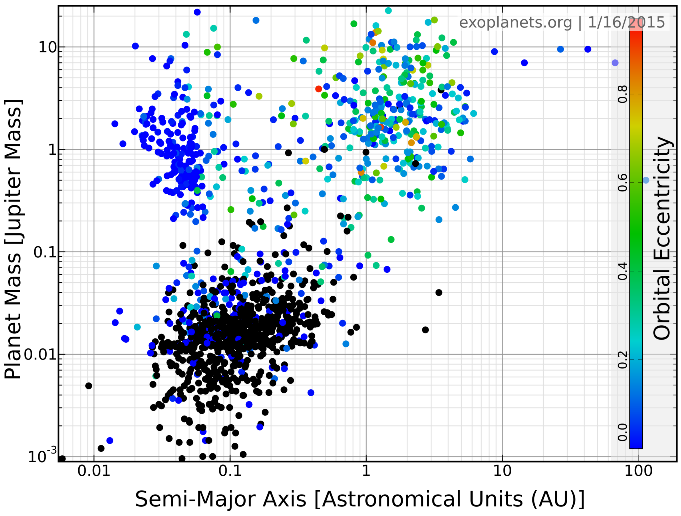

Figure 1: Currently known exoplanets, plotted as a function of semimajor axis and planetary mass with the color indicating their orbital eccentricity, when determined (courtesy of exoplanets.org).

Over the last ten years, nevertheless, observational, theoretical and laboratory efforts provided new data and ideas that enriched our understanding of planetary formation in the Milky Way. The

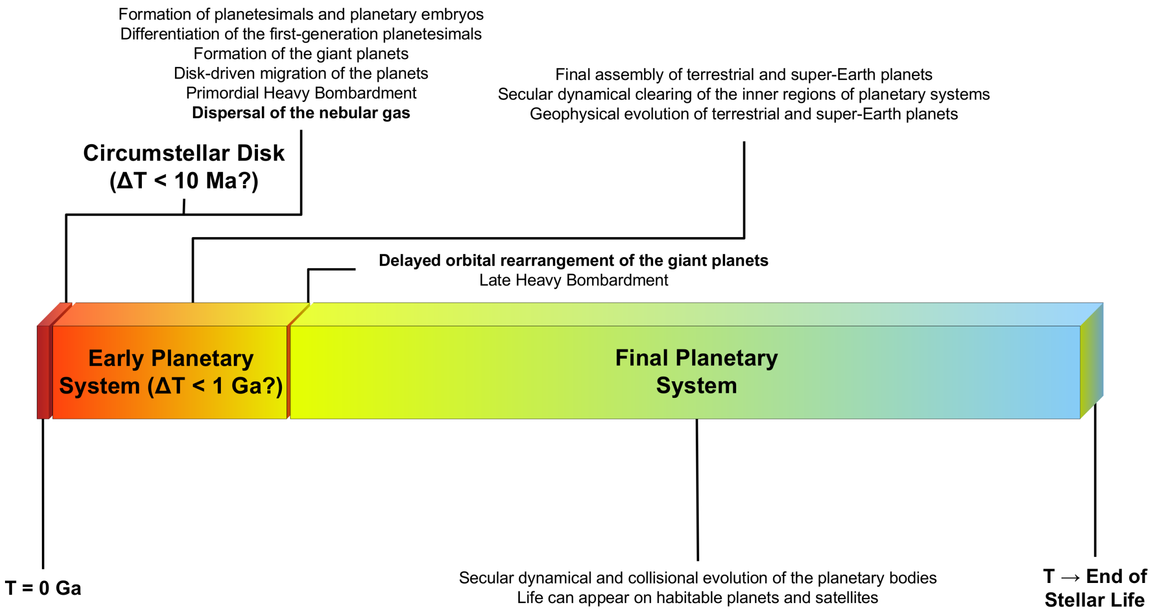

Figure 2: Timeline of a generic planetary system following the schematic division in three phases proposed by [11] for the Solar System. The events that mark the transition between the different phases are highlighted in bold characters.

aim of this paper is to provide an overview of these advancements based on the lessons taught us by extrasolar planets and the Solar System. For more detailed information on specific aspects, readers can find updated reviews on the formation of planetesimals and planetary embryos and their chronology from meteorites in [1],[2], [3] and [4], on the formation of the terrestrial planets in [5] and [6], on the formation of the giant planets in [7] and [8], and on the subject of planetary migration in [9] and [10]. Before proceeding it can be helpful to set a common temporal framework, valid both for the Solar System and extrasolar planets, that can be used as a reference point in the following discussion. We will adopt the schematic subdivision of the life of planetary systems in three phases presented by [11] and [12] and shown in Fig. 2. As can be seen from Fig. 2, these three phases have been labelled the *circumstellar disc*, the *early planetary system* and the *final planetary system*. As the name of the third phase suggests, the planetary formation process develops over the first two phases and its conclusion marks the beginning of the last one.

2. Timescales of formation of the planetary bodies

Planetary formation begins in circumstellar discs with the formation of the first solids bodies (see Fig. 2), which in the Solar System have been identified as the Calcium-Aluminium-rich Inclusions (CAIs in the following) found in chondritic meteorites. The oldest sample currently known in the Solar System sets the beginning of its formation to 4568.2 ± 0.1 Ma ago [13]. The duration of this phase of the history of a planetary system is constrained by the lifetime of the discs, which varies between 1-10 Ma with the median value being of about 3 Ma [14, 15]. In the case of the Solar System, indirect constraints from meteoritic data and theoretical studies favours the survival of the circumsolar disc for at least 3-5 Ma [16, 17] and a conventional value of 10 Ma is generally assumed in theoretical studies of planetary formation. During the few Ma of the life of circumstellar discs, several fundamental steps of the planetary formation process take place (see Fig. 2).

From the meteoritic data available for the Solar System we know that planetesimals, bodies ranging in size from a few hundreds meters to a few hundreds kilometres, appeared in the first 1-2 Ma after CAIs ([3], see Fig. 2). The fact that the oldest achondrites and iron meteorites predate the oldest chondrites [3] indicates that the first generation of planetesimals was able to differentiate [3, 18] due to the energy released by short-lived radioactive nuclei (mainly Al^{26} and Fe^{60}) while planetesimals that formed at a later time were not (see Fig. 2). Based on the result of thermal modelling, in order to be able to differentiate planetesimals should have been larger than about 20 km in diameter [3] and, if smaller that $\sim$500 km in diameter (i.e. about the size of asteroid Vesta), should have formed less than 1.5 Ma after the injection of the short-lived radionuclei in the circumsolar disc [19].

Contemporary to planetesimals also planetary embryos, bodies ranging in size between the Moon and Mars, were forming (see Fig. 2): this is confirmed by the study of martian meteorites that indicate that Mars should have reached about half its present mass in about 2 Ma after CAIs and should have completed its formation between 3 and 8 Ma after CAIs [20]. Finally, we know that giant planets should form in circumstellar discs (see Fig. 2) as H and He, which represent about 90% of the masses of Jupiter and Saturn, are present only in gaseous form at the typical conditions of circumstellar discs and are therefore lost to the planetary system after the dispersal of the nebular gas (see e.g. [8]). The data available for the giant planets in the Solar System [21] support their formation following the core accretion scenario (see e.g. [8] and references therein). This implies that bodies with masses several times larger than that of the Earth (akin to the largest super-Earths discovered around other stars) and capable of gravitationally trapping the nebular gas should also be able to form in circumstellar discs (see Fig. 2), i.e. in less than about 10 Ma.

While circumstellar discs can be the birthplace of all classes of planetary bodies, at least in terms of their mass, the planetary formation process does not stop with the dispersal of the nebular gas. Based on the data available for the Earth and Mars, terrestrial planets complete their formation and begin their geophysical evolution due to differentiation after the disc dissipates (see Fig. 2 and [6, 4] and references therein). Specifically, the radio-chronometric data available for the Earth locate its formation between 40 and 60 Ma after CAIs (see e.g. [6] ad references therein). Also super-Earths should complete their formation after the dispersal of the disc (see Fig. 2), especially the most massive of them: bodies with mass about five times that of the Earth, in fact, would start capturing gas from the disc to form a gaseous envelope should they form before its dispersal (see [7, 8] and references therein). Such planets would probably be more similar to smaller versions of the icy giant planets of the Solar System, Uranus and Neptune, than to terrestrial planets.

3. The formation of planetesimals and their initial size distribution

Together with the timescale of formation of the different classes of planetary bodies, also the size distribution of the first bodies to appear in circumstellar discs in general and in the Solar Nebula in particular was recently put into question. The classical point of view was that the coagulation of the dust populating a circumstellar disc into planetesimals required a quiescent disc, i.e. a disc were turbulence was limited or absent. This kind of nebular environment could allow for the collisional sticking of dust grains with each other in order to create porous meter-sized objects, which would then collisionally accrete smaller bodies and form the planetesimals (see e.g. [1, 2] and references therein). The lack of significant turbulence would also allow for the gravitational collapse of dust clumps under their own self-gravity, should they reach a critical density, to form planetesimals with size ranging between hundreds of meters to a few tens of kilometres [22, 23, 24]. In the last few years, however, it has been suggested that turbulence, contrary to what was previously thought, could actually play an active role in the building of the primordial planetesimals by locally enhancing the dust concentration up to the critical values needed to trigger self-gravitation [25, 26, 1]. The proposed turbulence-assisted mechanisms for planetesimal formation differ significantly from those associated instead to a quiescent disc in terms of the size distribution they produce. Instead of meter-sized to km-sized objects, the first generation of planetesimals could range directly from a few tens to a few hundreds of kilometres [25, 26, 27]. A comparison of the average masses and diameters of the planetesimals estimated throughout the Solar Nebula as a function of their radial distance from the star in the quiescent and turbulent cases (as derived respectively from [24] and [27]) is shown in Fig. 3.

Interestingly enough, simulations [28, 29] showed that all these different initial size distributions of the planetesimals would quickly tend to converge toward a similar collisionally evolved size-frequency distribution after a few Ma (1-3 Ma according to [28]), in agreement with the timescales derived from meteorites described in Sect. 2 and shown in Fig. 2. This collisionally evolved size-frequency distribution would be dominated in number by small (< 10 km in diameter) planetesimals and in mass by large (> 1000 km in diameter) planetesimals and planetary embryos [29, 28].

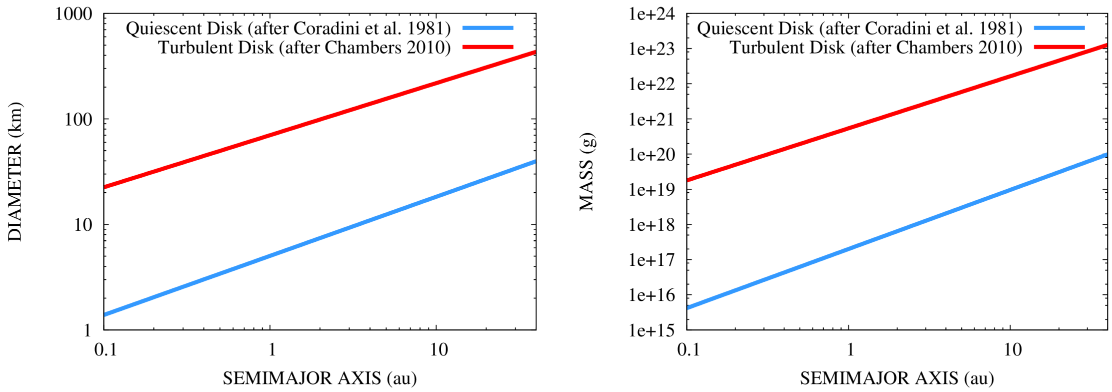

Figure 3: Left plot: average diameter of the planetesimals throughout the circumstellar disc in a quiescent and a turbulent disc based respectively on the results of [24] and [27]. Right plot: average masses associated to said diameters assuming a constant density of 3 g cm^3.

4. The formation and migration of the giant planets

The fact that giant planets played a major role in shaping the current structure of the Solar System has been recognized since 1950-1960 (see e.g. [22] and references therein), but in recent years three sets of theoretical works provided new insight on the role the giant planets had in the formation and evolution of the Solar System. In the chronological order in which the events they describe took place, these theoretical works are: the Jovian Early Bombardment model [31, 32, 33, 34, 35], the “Grand Tack” scenario [42, 43, 44], and the “Nice Model” [45, 46, 47, 48, 49]. The events at the basis of the first two of such works occur during the life of circumstellar discs (see Fig. 2), while the third one is generally held to represent the landmark, in the Solar System, of the passage between the second and third phases (early and final planetary system) described in Fig. 2.

4.1 The Jovian Early Bombardment

As originally recognized by the pioneering works of [22] and [30] for the case of Jupiter, the formation of giant planets triggers a phase of intense remixing of the solid material in the circumstellar discs they are embedded in and a bombardment of the other planetary bodies populating the forming system (see [22, 30, 36, 31, 32] and Fig. 2). The bombardment is caused by the interplay between the gravitational scattering of planetesimals near-by the newly formed giant planet and the appearance of the orbital resonances in regions farther away (see Fig. 4 and [22, 30, 36, 31, 32, 33, 34]. As this process was first studied focusing on Jupiter and the Solar System, this model was named the Jovian Early Bombardment [31, 11, 32, 33, 34]. However, since the processes at the basis of the Jovian Early Bombardment model are general to all planetary systems hosting a forming giant planet, [11] and [32] pointed out that the Jovian Early Bombardment represents a specific case of the general class of phenomena they called the Primordial Heavy Bombardment, by analogy to the more studied Late Heavy Bombardment (see Sect. 4.3), which can involve more than one giant planet at the same time. The duration of the phase of bombardment and remixing triggered by the formation of Jupiter was estimated to be about 0.5-1 Ma [30, 31, 32]. While the duration of the Jovian Early Bombardment is quite limited (about an order of magnitude shorter than the one of the Late Heavy Bombardment in the “Nice Model”, see Sect. 4.3) its effects are not, due to the larger population of planetesimals and planetary embryos existing at the time.

First, the Jovian Early Bombardment causes a significant mass loss to planetesimals as large as about 500 km in diameter [32, 33, 34] in the orbital region of the asteroid belt. Contrary to what occurs at later times and on secular time-scales where catastrophic impacts dominate the mass loss process [50, 51, 52], this mass loss is due to the process known as cratering erosion [50], i.e. the cumulative mass ejected at velocities higher than the escape speed of the target body by non-catastrophic impacts. Second, the Jovian Early Bombardment injects volatile-rich planetesimals formed beyond the water ice condensation line into the inner Solar System or at the very least into the orbital regions of the asteroid belt and Mars [30, 36, 31, 32]. Impacts can then deliver water and volatile materials to the largest planetesimals (i.e. those not eroded or shattered by the bombardment) and to planetary embryos [34], in agreement with the global picture supplied by the observational results of [53], which attributes an important role to comets in the delivery of water to the inner Solar System. Finally, the Jovian Early Bombardment causes an enhanced rate of impacts on Jupiter itself: planetesimals and planetary embryos colliding with the giant planet deliver both volatile and refractory materials into its atmosphere, enriching it in high-Z elements (see e.g. [35] and references therein) in agreement with what is indicated by observational data (see [54, 21, 55]). The entity of the latter effect of the Jovian Early Bombardment, however, does not appear to be able to explain by itself the measured enrichments (see [35]), although to date it has undergone only a preliminary investigation under simplified assumptions and the resulting enrichments could be significantly underestimated.

According to the results of [22, 30, 36, 31, 32, 33, 34, 35] the formation of a giant planet is the sole and necessary condition to trigger the bombardment and remixing phase described by the Jovian Early Bombardment model. Nevertheless, orbital migration can significantly influence both the intensity and effects of the Jovian Early Bombardment (see Fig. 4, Fig. 5 for an example of the influence of migration for the effects of the Jovian Early Bombardment on asteroid Vesta, and [31, 32, 33, 34, 35] for a discussion). All works focusing on the Jovian Early Bombardment performed to date took place in the framework of the classical scenario for the formation and evolution of the Solar System, which meant that Jupiter should have concluded its inward migration at or near its current orbital location. In this framework, the investigation of the collisional (i.e. cratering erosion and excavation of the basaltic surface) and compositional (i.e. delivery of water and volatile elements) implications of the Jovian Early Bombardment on asteroid Vesta[1] suggest that Jupiter should have undergone a moderate (0.25-0.5 au) migration after its formation (see Fig. 5 and [33, 34] for details).

4.2 The “Grand Tack” scenario

A long standing challenge in explaining the formation of the terrestrial planets in the framework of the classical scenario was posed by the low mass of Mars. In the classical scenario there is no *a priori* reason, except stochastic effects, for the growth of this planet to have stopped at the stage of a planetary embryo, escaping any giant impact with similarly sized bodies during the time it took for the Earth to form. A possible way out of this problem was proposed by [57] who showed that, should the mass necessary to form the terrestrial planets be concentrated inside 1 au ([57] postulate between 0.7 and 1 au), this would systematically result in planetary bodies no larger than planetary embryos in the orbital region of Mars due to their dynamical diffusion outside of the region originally populated by the planetesimals and the planetary embryos.

There is no specific reason why the such an initial concentration of mass should naturally occur in a circumstellar disc, unless some external forcing caused it from an initially continuous radial distribution of planetary bodies. A possible cause for such an arrangement was suggested by [42] to be linked to an early extensive migration of the giant planets. In what they called the “Grand Tack” scenario, [42] postulated that Jupiter and Saturn could have undergone a initial inward migration that brought Jupiter to about 1.5 au from the Sun, effectively truncating the disc of planetesimals at 1 au. Saturn, while forming later than Jupiter, would have migrated faster due to its lower mass and would have caught up in a resonant configuration with the former. In this configuration the gaps opened by the giant planets in the circumstellar disc would have overlapped forming a single shared one.

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[1] Asteroid Vesta is the most ancient body for which we possess samples, in the form of the Howardite-Eucrite-Diogenite (HED) family of meteorites, that provide us with detailed compositional and chronological information on its evolution. Specifically, HED meteorites reveal us that Vesta has a ~ 30 km thick crust that formed in the first 3 Ma of the life of the Solar System [39, 40] and, as showed by the NASA mission Dawn, survived until now [37, 38]. HED meteorites also tell us that, while Vesta is a globally volatile-depleted body, small amounts of water were delivered into its molten crust before it completely solidified [41].

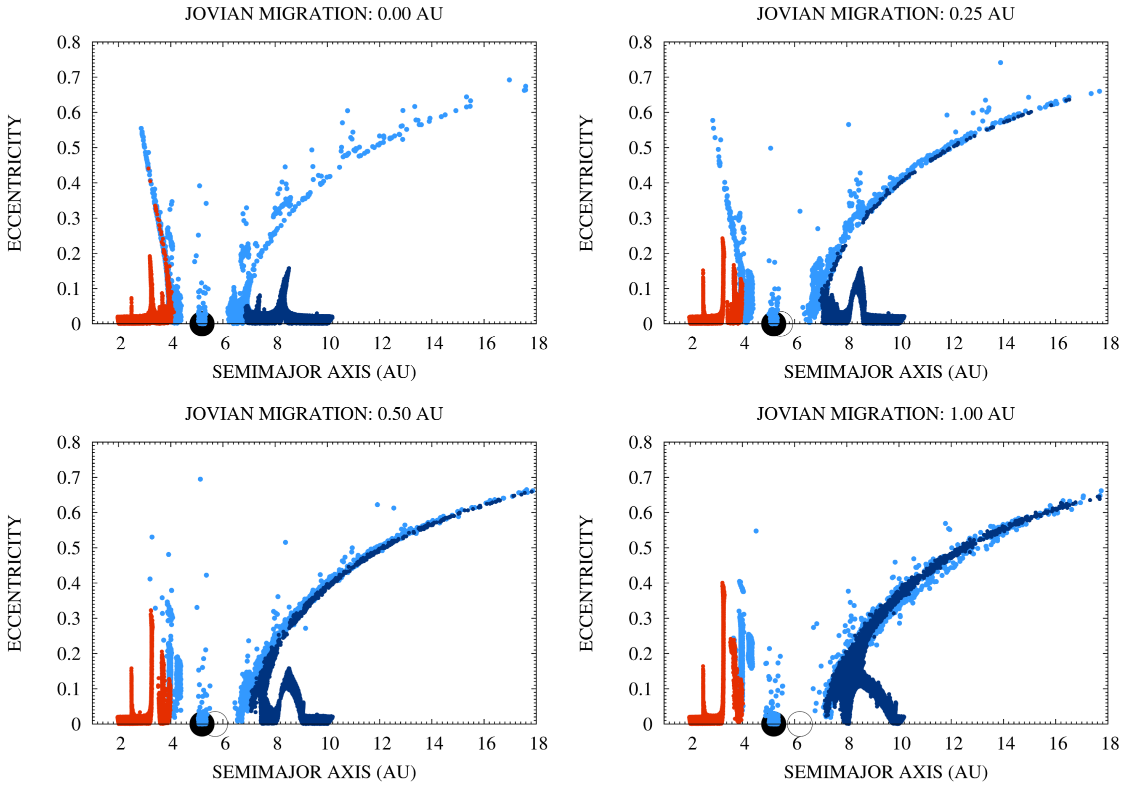

Figure 4: Orbital distribution of the Solar Nebula $2x10^5$ years after the beginning of the accretion of the nebular gas by Jupiter, i.e. during the Jovian Early Bombardment, in the simulations performed by [31]. The cases considered encompass the classical scenario with no migration (top left), moderate migration (0.25-0.5 au, top right and bottom left) and extensive migration (1 au, bottom right). Planetesimals that formed between 2 and 4 au are indicated in red, those that formed between 4 and 7 au in light blue and those that between 7 and 10 au in dark blue. The open circles are the positions of Jupiter at the beginning of the simulations, the filled ones are the position of Jupiter once fully formed. In the case of no migration, the excited (light blue) planetesimals outside 6 au represent the outward flux predicted by [22] while those inside 4 au represent the inward flux first discussed by [30].

Due to the unbalance between the torques exerted on the giant planets by the disc at the edges of the common gap and the fact that the resonant configuration effectively couples the two planets in their dynamical evolution, the two giant planets would experience a phase of outward migration that would have moved them toward their actual orbital positions ([42] postulate the ones predicted by the “Nice Model” for before the Late Heavy Bombardment, see Sect. 4.3). During this inward-then-outward migration, the two giant planets would deplete and then replenish the orbital region of the asteroid belt, populating its inner and outer parts with bodies coming respectively from the inner and outer Solar System [42, 43]. Water-rich bodies from the outer Solar System would also be injected inside 1 au and be incorporated into the forming terrestrial planets [44].

Even if the study of the Jovian Early Bombardment in the framework of the classical scenario suggest that Jupiter underwent a moderate migration, the “Grand Tack” scenario is not inconsistent with the Jovian Early Bombardment model. Actually, it implies a stronger and longer phase of

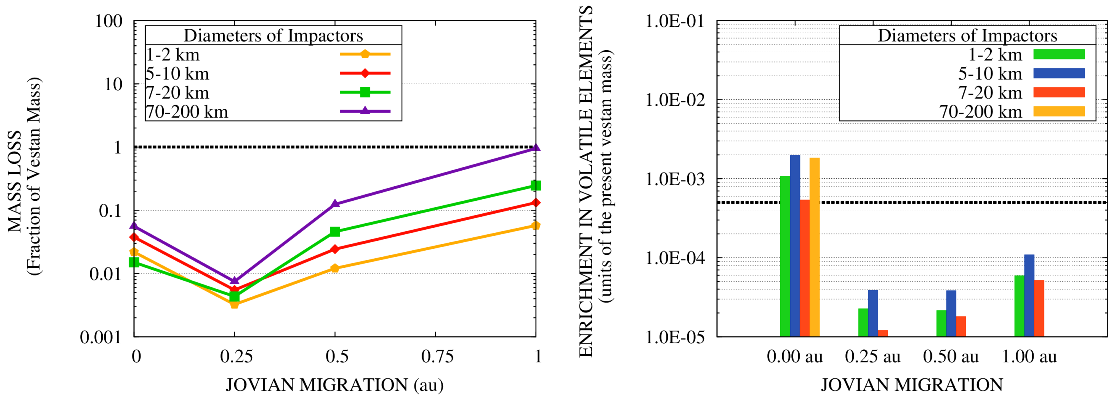

Figure 5: Mass loss (left plot) and enrichment in volatile elements (right plot) of Vesta based on the results of [33, 34] for different sizes of the primordial planetesimals impacting Vesta during the Jovian Early Bombardment. The horizontal line in the right plot is the water fraction of the Earth (5×10^{-4}) from [56]. A non-migrating Jupiter would deliver too much water to Vesta (see right plot) while a jovian migration of 1 au or higher would cause too high mass loss for the vestan crust to survive up to now (see left plot). As a result, in the framework of the classical scenario the cases most consistent with our knowledge of Vesta are those of moderate (0.25-0.5 au) migration of the giant planet.

bombardment than the one associated to the classical scenario. At the beginning of the simulations performed by [42] Jupiter is already fully formed, which means that the Jovian Early Bombardment has already been triggered by the sudden mass increase of the planet and its possible migration during the gas accretion phase. However, as pointed out in Sect. 4.1, migration plays an important role in enhancing the duration and the intensity of the bombardment, which should extend across the whole inward migration phase and, to a lower extent due to the depleted population of the disc, during the outward one.

4.3 The "Nice Model"

The third theoretical work we mentioned in Sect. 4, the so called "Nice Model" [45, 46, 47, 48, 49], is the one that occurred the latest in the history of the Solar System and that was formulated the earliest of the three here discussed. The "Nice Model" proposes that the Solar System underwent a late phase of dynamical instability, temporally located about 700 Ma after the formation of the giant planets and the events described in the Jovian Early Bombardment model and the "Grand Tack" scenario, which was suggested to have been responsible for the event known as the Late Heavy Bombardment, a period of proposed increased impact flux on the Moon and the terrestrial planets (see e.g. [58, 59] and references therein for an in-depth discussion of the evidences in favour and against the Late Heavy Bombardment).

In the "Nice Model" the giant planets of the Solar System are postulated to be located, after they concluded their formation and disc-driven migration, on a more compact orbital configuration than their present one and to interact with a massive primordial trans-Neptunian region. The gravitational perturbations among the giant planets are initially mitigated by the massive trans-Neptunian disc, whose population in turn is slowly eroded. Once the trans-Neptunian disc becomes unable to mitigate the effects of the interactions among the giant planets, the orbits of the latter become excited and a series of close encounters takes place. The net result of the ensuing planet-planet scattering (also known as "Jumping Jupiters" process, [60, 61]), in those scenarios that reproduce more closely the present orbital structure of the Solar System, is a small inward migration of Jupiter and marked outward migrations of Saturn, Uranus and Neptune [47, 49], with the Jupiter-Saturn separation globally increasing by about 1 au and a large chance ($\sim$ 50%) of Uranus and Neptune swapping their orbits.

From an historical point of view the "Nice Model" represents a landmark for our way of viewing at the evolution of planetary systems: while not the first attempt to include extensive migration of the giant planets in the Solar System, it was to date the most successful one and allowed for bridging the gap between the violent and chaotic picture derived from the orbital features of the extrasolar planets and our knowledge of the past of the Solar System. From the experience of the "Nice Model" we learned in fact that the Solar System is one of the possible outcomes of the sequence of events that collectively shape the formation and evolution of planetary systems, but does not necessarily need to be the product of different processes than the ones that shaped the known extrasolar planetary systems.

5. A look toward the future

As we discussed in this paper, over the last ten years new data and ideas changed our view of planetary formation and showed us that the knowledge derived from the study of the Solar System and the one we gather from the investigation of extrasolar planets are not necessarily at odds. Each individual planetary system might tell us a different story, but the ingredients that are mixed together in order to produce it are the same. While it is difficult, not to say impossible, to predict which new ideas and discoveries will challenge our current understanding in the coming years, there are two things that we can confidently say.

The first one is that in the coming future the study of planetary formation will see the fields of Solar System and extrasolar planets more and more strictly connected: as we said at the beginning of the paper, what extrasolar planets can offer in terms of statistics of the possible outcomes of the planetary formation process, they lack in terms of details. On the other side, the richness of detailed information we can derive from the Solar System unluckily refer to only one of those possible outcomes. In order to progress in our understanding of planetary formation in our galaxy we will need all the information we can gather from both fields of study.

The second one is that, in order to be able to increase our understanding of planetary formation, future studies will need to take as much advantage as possible from the combined information provided by orbital data and the composition of planetary bodies. The orbital information alone, in fact, does not provide enough constraints to solve the intrinsically degenerate problem of unveiling the past history of a planetary system from its current state. As an example, extensive planetary displacements can be the result of either a very early phase of disc-driven migration or of late planet-planet scattering events. The composition of a planetary body, however, is strongly linked to that of its formation region and to its dynamical evolution and can therefore provide the missing constraints we need to solve the puzzle posed by its origin and past history.

DISCUSSION

BORIS SHUSTOV (Institute of Astronomy - Russian Academy of Sciences):

You concluded that currently know exoplanets and exoplanetary systems seem to live in quite different mode in comparison to the Solar System. But the existing techniques of discovery are strongly biased by observational selection. Do you think that coming massive discoveries of exoplanets may confirm that the evolution of the Solar System is not an exception but "main stream"?

DIEGO TURRINI:

The issue of how representative is the current samples of exoplanets is critical when it comes to understand the place of the Solar System in the galactic context. The sample we know to date clearly provides only a partial view because of the selection effect of the observational constraints, but it seems to indicate the the outcomes of the formation and dynamical evolution of planetary systems represent a continuum. Should this prove true, it would mean that the Solar System does not represent a special case and that the conditions needed to produce it (and, with it, habitable environments and possibly life) are hard-wired into the processes of stellar and planetary formation.

IVAN ALMAR (Konkoly Observatory of the Hungarian Academy of Sciences):

I also wanted to emphasize the issue of the “selection effect”, because at present neither the transit nor the Doppler method is able to discover a planetary system like our Solar System. Have you any guess when such a discovery will be possible, let us say, from a few hundred light years?

DIEGO TURRINI:

This question is easier to answer in terms of single planets rather than of planetary systems. We currently do have the observational capabilities and temporal baseline to identify exoplanetary analogues of Jupiter (both in terms of mass and orbit) but not of Saturn, Uranus and Neptune. Two space mission, NASA’s Transiting Exoplanet Survey Satellite (TESS) and the ESA’s Plato, are currently planned for launch in 2017 and 2024 respectively: they should allow for the identification of exoplanetary analogues of the Earth. It wouldn’t therefore be too surprising should the first, partial analogues of the Solar System (i.e. without the ice giants Uranus and Neptune and the smaller planets like Mars and Mercury) be discovered during the second quarter of the century.

WOLFGANG KUNDT (Argelander Institut of Bonn University):

Can you provide more details on what is the source of the angular momentum during the outward migration of Jupiter and Saturn in the “Grand Tack” scenario?

DIEGO TURRINI:

The angular momentum is supplied by the circumsolar disc and is transferred between the two planets by a mean motion resonance. The outward migration is in fact a direct result of three factors: i) the two giant planets are in or close to a mean motion resonance; ii) while they are in this configuration their gaps partially overlap; iii) the outermost planet (Saturn) is less massive than the inner one (Jupiter). Because of the overlap of the gaps, Jupiter experiences a larger positive torque from the inner region of the circumsolar disc (the density of the gas outside Jupiter’s orbit is lowered by the presence of Saturn's gap) and is forced to migrate outward. Saturn experiences a similar but opposite effect (the imbalance is in favour of the negative torque caused by the outer region of the disc). The fact that the two giant planets are in resonance effectively couples their dynamical evolution and makes them behave as a single body (at least for the purposes of the migration): because of the larger mass of Jupiter, its positive torque dominates and the two giant planets jointly migrate outward.

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