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Did a stellar fly-by shape the outer solar system?

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Abstract

In contrast to the planets, the transneptunian objects (TNOs) mostly move on inclined, eccentric orbits. This implies that some process restructured the outer solar system after its formation. As some TNOs move outside the zone of influence of the planets, external processes might have played an important part in structuring the outer solar system. Here we show that a close fly-by of a neighbouring star can simultaneously produce not only many of the TNO features but also the family of Sednoids, which are otherwise difficult to explain. In the past it was estimated that such close fly-bys are rare during the relevant development stage. However, our computer simulations show that such a scenario might be much more likely than previously assumed.

1. Introduction

There are several features of the solar system that seem at odds with the simple picture of forming from a smooth disc surrounding the young Sun and staying that way afterwards. First, the surface density of the solar system drops by a factor of more than 1000 outside Neptune's orbit at 30 AU. Second, most TNOs move on eccentric, inclined orbits (i $>$ 4°) relative to the planetary plane. Third, such objects exist even outside the range of influence of the planets. All three points strongly indicate that the outer reaches of the solar system must have been considerably modified by some process(es) that took place after its formation.

Here we suggest that the Sednoids would have been excited to their current orbits by the close fly-by of a star. However, in contrast to the sometimes invoked capture scenario [4, 5, 1], here the Sednoids would originate from the Sun's own once more extended disc.

2. Fly-by parameter range

We simulate the Sun as being surrounded by a disc of test particles. This disc could represent either a protoplanetary or a debris disc, the inner part might even contain the already formed planets. We modelled fly-bys with perturber masses of 0.3, 0.5, 1.0, 2.0 5.0, 10. 20, 50 M_{sun} at periastron distances of r_{peri}= 30, 50, 100, 150 200, 300, 500, and 1000 AU. The parameter space in orbital inclination was covered in steps of 10° and the angle of periastron in steps of 30°.

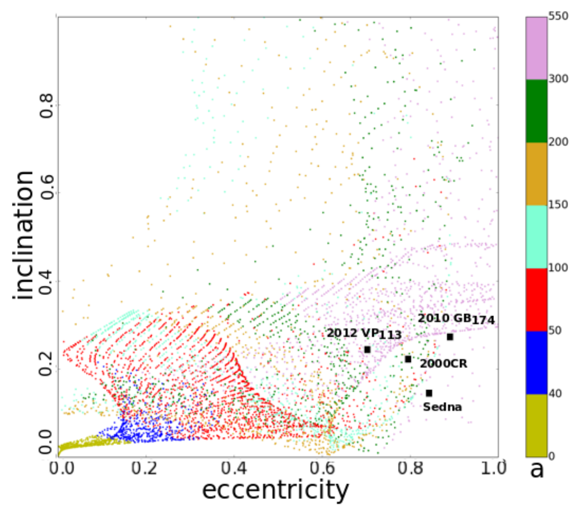

Figure 1: Inclination vs. eccentricity of all test particles in a fly-by with m_p=0.5 M_{sun} on an inclined orbit (60°) with an angle of periastron of 90° passing the Sun at 100 AU. The colours are representative for a.

Of all these parameter combinations the best match to the observed properties is found for the fly-by of a star of mass m_p=0.5 M_{sun} on an inclined orbit (60°) with an angle of periastron of 90° passing the Sun at 100 AU, that was initially surrounded by a 150 AU-sized disc. There have been previous simulations [2, 6] with similar parameters which found neither a cold Kuiper belt population nor Sedna-like objects. The reason is probably too low resolution in the outskirts of the disc and a too small initial disc size.

A fly-by with the parameters in this parameter range reproduces many of the features of the outer solar system all in one go. Not only does it reproduce the hot and cold Kuiper belt population and the Sednoids, but also the new family of TNOs which have relatively large periastra but low eccentricities [7] and gives an explanation for Neptune being more massive than Uranus. Thus this model fulfils two demands on a new theory - it agrees largely with the available data and it is simpler than existing models. The question is now: Is it also likely that such an event has actually taken place?

3. Fly-by probability

Given that 90% of the Milky way clusters largely dissolve within 10 Myr [3] , it is often assumed that basically no close fly-bys happen afterwards. This is the main reason why previous suggestions of fly-bys possibly being responsible for the properties of the outer solar system have received not much attention. We model the frequency of clusters similar to the Orion Nebula cluster (ONC) throughout the different clusters phases - embedded, gas-expulsion, expansion and new semi-equilibrium phase. Fig. 2 shows that although the fly-by frequency that leads to the solar system features are highest in the initial 1-2 Myr, afterwards fly-bys do happen also at a much lower rate. Thus we find that such type of fly-bys are probable not only during the early phases but also on Gyr time scales, with a 5-7% probability during the first 10 Myr and a 20-30% chance in the next Gyr.

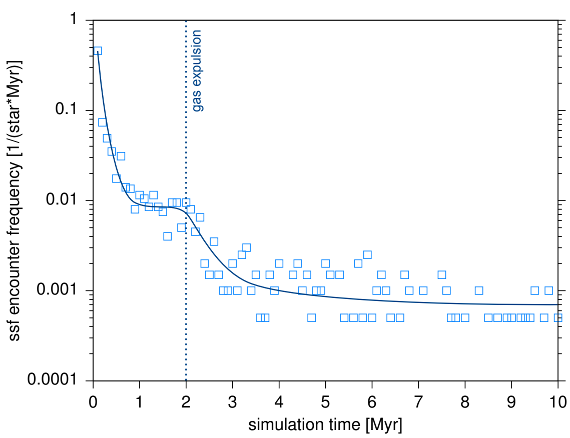

Figure 2: Frequency of fly-bys with the parameters of Fig.1 as a function of time since cluster formation for an ONC-like cluster.

It is often argued that in the outer regions of the solar system objects would require well over 10 Myr to grow to their current size and at that time fly-bys would be extremely rare. However, newly available high-resolution images of discs around stars younger than 10 Myr show prominent ring structures at several 10s to 100s AU and beyond. Many authors interpret these as signatures of already formed or currently forming planets. If gas giants can form at such distances from their host star in such a short time span, it can no longer be excluded that TNO-sized objects can also form on time scales < 10 Myr. This means that a solar system forming fly-by could have happened either during the first 10 Myr or afterwards.

4. Summary and Conclusions

We found that fly-bys of stars with masses in the range 03.-1.0 M_{sun} at perihelion distances of between 50 and 150 AU inclined between 50 to 70 degree and tilted between 60 to 120 degree are the most promising candidates for shaping the outer solar system. Such fly-bys lead to Sednoids, a hot and cold Kuiper belt population and various other properties characteristic for the outer solar system. What distinguishes this model from others, is that only a single event is necessary to create all this features. Thus the beauty of this model lies in its simplicity. We fi

nd that such type of fly-bys are probable not only during the early phases but also on Gyr time scales, with a 5-7% during the first 10 Myr and a 20-30% chance in the next Gyr. This probability of such an event is competitive to that of other models for origin of the outer solar system features. The strength of this hypothesis lies in its simplicity by explaining several of the outer solar system features by one single mechanism.

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Derivation of gas and dust surface fluxes on comet 67P

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In August 2014 the ESA Rosetta space probe approached less than 100 km to the nucleus of comet 67P/Churyumov-Gerasimenko (67P), when it was at 3.00 AU from the Sun. During the following several months it gathered information on the dusty-gas atmosphere in the immediate vicinity of the nucleus.

We describe the models developed to predict the gas and dust environment of comet 67P and their methods of adjustment to the observational data obtained by Rosetta before its lander Philae landed on 67P surface.

Ideally speaking, the optimization of the gas model would have resulted from a succession of predictions of the local gas parameters along optimal Rosetta trajectories, as well as of the gas parameters inside the field-of-view of the remote-sensing instruments, followed by the comparison with the in-situ and remote-sensing instruments data. This turned out to be impossible for many reasons. Actually, predefined Rosetta trajectories and instrument view directions turned to be non-optimal for adjusting the model parameters. Therefore, we focused on: (1) fitting the measurements performed by the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) [1] with the gas model, and (2) fitting the dust coma images acquired by the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) [4], taking into account the dust size distribution (see [3]) obtained by the Grain Impact Analyser and Dust Accumulator (GIADA) [2], with our dust model.

We present the resulting distribution of gas and dust fluxes over 67P surface.

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Asymptotics for spherical particle motion in a spherically expanding flow

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In the context of an increasing number of complex multiparametric dust coma models, it was found convenient to construct an elementary model with a minimum number of parameters selected to represent the key processes acting on the dust (see [1]). The model outputs can be used as a reference evaluation of these processes with rough estimates of the resulting dust properties, e.g. velocity. The present work introduces three universal and dimensionless parameters, which characterize the dust motion in an expanding flow and computes, as a function of these parameters: 1) the dust terminal velocity; 2) the time to acquire it; and 3) the distance at which it is acquired. The motion of dust grains is presented as a system of dimensionless ordinary differential equations, the solution of which depends upon the above mentioned three parameters. The numerical integration of this system was performed over a wide range of parameter space covering the whole range of physically possible conditions. Precomputed results of dust terminal velocity, time and distance at which it is reached are presented in dimensionless form. To obtain dimensional values for a particular case it is sufficient to perform algebraic operations.

In agreement with our model: 1) GIADA dust particle speed measurements are consistent with the calculated terminal velocities; 2) OSIRIS data constrain the dust acceleration limited within six nuclear radii for a broad range of particle sizes.

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The cradle of the Sun

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Abstract

Most stars form not in isolation but as part of a group of stars referred to as cluster or association[2]. There are many indications that the Sun also formed as part of such a group of stars. Here we investigate what the most likely birth environment for the Sun was. We first show that there are basically two kinds of stellar groupings - clusters and associations. These two groups significantly differ in their temporal development and most importantly in the way the stellar density changes over time. We perform simulations of these different type of clusters and determine the frequency of potentially solar system shaping events. With these simulations we can narrow down the extensive mass radius regime of existing clusters to just two cases that of potential environments of the early solar system - these are (i) massive associations with $>$ 10 000 stars but relative large initial half-mass radii of over 1 pc or (ii) less massive ($\sim$ 1000 stars) compact clusters with initial half-mass radii in the range 0.1-0.3 pc.

1. Introduction

Most stars are born in groups, which formed from dense cores in giant molecular clouds (GMCs). Here we want to investigate in how far interactions with the other groups members potentially shape the resulting planetary systems and in particular our own solar system. Such stellar groups can be divided in two categories - clusters and associations. Where clusters are considerably are more compact and therefore have a much higher stellar density than associations of the same age. However, both are highly dynamical entities and are there density develops considerably over the first 10-20 Myr [3]. Fig. 1 shows the density development in these two groups as a function of cluster age.

There are many indications that the solar system also formed in a cluster[1]. For example the steep drop in mass density at 30 AU in the solar system is often interpreted that an external process lead to disc truncation at such a size. Basically two external processes could lead to such disc truncation either a stellar fly-by external photo evaporation. The former would be just induced by the gravitational effect of a passing neighbouring star, the latter by the radiation of a nearby massive star. Both processes are most likely in stellar groups that contain at least a few hundred members. Here we mainly concentrate on the case where a stellar fly-by caused such a disc truncation. We ask the question what kind of star cluster would have been the most likely birth environment of the Sun.

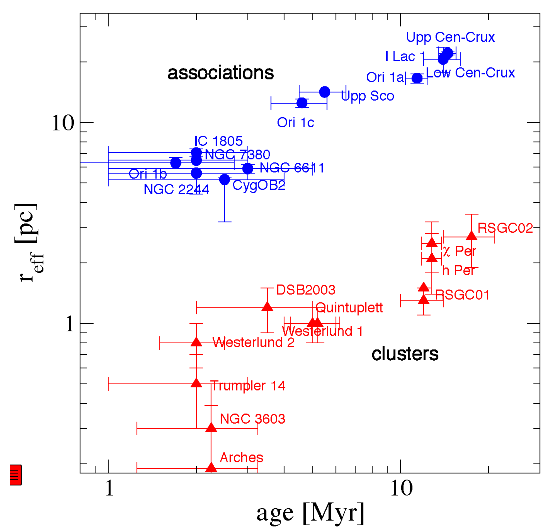

Figure 1: Half-mass radius vs. age of young stellar groups showing the distinct differences in development between associations and clusters.

2. Method

We performed two type of simulations to determine the effect of stellar fly-bys on early solar systems. First, we simulate the dynamics of stellar clusters and associations reproducing the two typical temporal sequence shown in Fig. 1. In each of these simulations we recorded the parameters of each close stellar fly-by.

Second, we performed an extensive parameter study of the effect parameter study that gives the various effects of such a fly-by on a protoplanetary disc or an already formed planetary system. In a last step we analyse just the solar type stars and determine the likelihood for a cut-off at 30 AU.

3. Results

As to be expected, close fly-bys are much more common in massive dense clusters than in associations, which have lower stellar densities. The perturbers in dense clusters are usually of equal or lower mass than the Sun. Differences can also be found concerning the eccentricity of the solar system forming fly-bys. In associations mots fly.bys occur on nearly parabolic orbits whereas in dense clusters this is not the case. Three- or many-body interactions happen relatively often in such dense environments.

The Sun is not part of an association today, which could be a result of the birth association's disruption due to the galactic field[4] or gas expulsion [3], after which only between 10-20% of all stars remain behind as a bound remnant. Even these remnant cluster might dissolve completely on time scales of 100 Myr or longer. The number of solar-system analogues which are ejected from an association after 20 Myr is even for the most massive association 104 -117 systems.

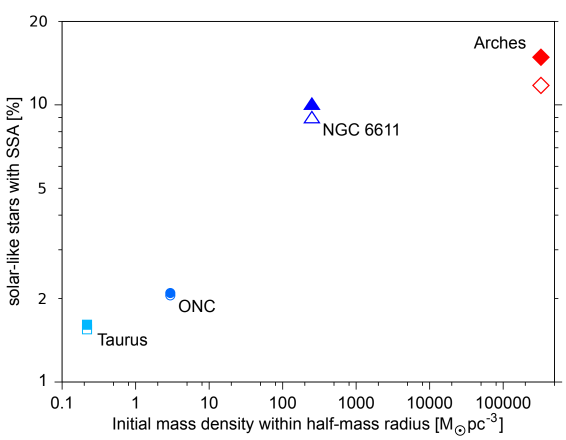

Figure 2: Frequency of solar sytem forming fly-bys of average cluster density: Example clusters are indicated.

The Arches-like cluster produces nearly twice the number of solar system analogues (SSA) as the NGC 6611 model, 250 after 3 Myr. However, in contrast to NGC 6611, this number decreases slowly with time, so there will roughly 210 systems left after 10 Myr. Clusters similar to our model (SFE = 70%) lose up to 15% of their stellar mass within the first 10 Myr after star formation, mostly due to stellar interactions. This means that about 32 SSAs would be ejected after 10 Myr. This number seems quite small, however, the clusters continue to lose stars with time due to stellar interactions, so the total number of ejected systems increases with time, e.g. 42 (20%) ejected SSAs at 20 Myr.

The position at which most solar system forming fly-bys occur varies strongly among the different association and cluster models. The Taurus model reacts slowest on the gas expulsion, therefore, most fly-bys occur around 0.1-0.3 pc.

4. Summary and Conclusions

Is it more likely that the solar system was born in an association or a stellar cluster? This question cannot fully be answered yet, as here only the initial 10 Myr have been modelled, over the following 4.5 Gyr still stellar fly-bys happen which could further alter the systems. However, solar-system analogues in "small" associations are - in terms of absolute numbers - quite rare because naturally the absolute number of solar-like stars increases with the number of association/cluster members and discs in such systems usually remain larger than 50 AU. Quantitatively, the absolute number of SSAs in Taurus-like environments is on average less than 1, in an ONC-like associations 4, and it increases significantly in very massive association like NGC 6611 to roughly 130, see also Figure 2.

Summarising, the solar system was most probably born in a massive association like NGC 6611 or a cluster like Arches. It is important to note, however, that we only consider the formation and destruction of SSAs by stellar fly-bys. Other effects, like for example external photo-evaporation, have to be taken into account to finally answer the question where our solar system was born.

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Dust dynamical traceback problem for derivation the surface properties of 67P/Churyumov-Gerasimenko based on the GIADA measurements

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Abstract

One of the intriguing questions to be answered with Rosetta space probe dust data is to determine the locations on the nucleus from where the observed dust grains were ejected and consequently to investigate on the 67P/Churyumov-Gerasimenko (67P) nucleus properties. The solution of this traceback problem requires 3D+t dusty gas model able to reproduce the measurements performed by various instruments onboard Rosetta.

As a first step, we use the GIADA (Grain Impact Analyser and Dust Accumulator) [1] in-situ dust measurements to trace the grains back to the nucleus using an inverse computation of trajectories of single grains having physical properties as measured by the instrument. We adapted our nonspherical dust dynamical code [2] to compute the trajectory of single dust grain back to the nucleus first solving the direct problem of GIADA dust particle motion in a simplified gas coma as in [3].

The resulting map of all GIADA particles on the 67P nucleus surface will be discussed as a preparatory strategy to tackle the trace back problem. This strategy will be compared with a new one that can resolve the trace back with a statistical approach. The latter looks for the most probable location on the comet nucleus from where the dust particle is emitted, the solution being a probability map for one particular family of emitted grains.

Acknowledgements

GIADA was built by a consortium led by the Universitá degli Studi di Napoli ‘Parthenope’ and INAF – Osservatorio Astronomico di Capodimonte, in collaboration with the Instituto de Astrofisica de Andalucia, Selex-ES, FI and SENER. GIADA is presently managed and operated by IAPS-INAF.

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Study on Statistical Properties of Asteroid Orbits Approaching Earth

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Abstract

To study the statistical properties of orbits of asteroids, a database site cneos.jpl.nasa.gov on 17.04.2018 and on 26.07.2015 was used. Distribution function of absolute stellar magnitudes is bimodal, the parameters of two Gaussian approximations are calculated. Gaps in the distribution of semi-major axes, corresponding to resonances with Jupiter 6: 1, 9: 2, 4: 1 are discovered. Extremum values of the orbital characteristics of asteroids and correlation factors between orbital elements are computed. Statistical characteristics for groups of Amors, Apollos, Atens, and also for asteroids with the probability of collision with the Earth more than 10^{-7} are found separately.

The characteristics for the catalogs are compared on July 26, 2015 and April 17, 2018.

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Modelling the Distribution of Comets in Extrasolar Systems

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Abstract

In the last years observations of absorption lines in spectra of stars varying on short time scales accumulate. Scientists refer to these findings as features caused by objects evaporating material on their orbit close to the star and thus call them comets in exo planetary systems – *exocomets*.

The aim of our investigation is to find a statistical model for the scattering of small objects which shows the most probable whereabouts of these objects after the gravitational interaction with planets.

We discuss the effect of different forces acting on the comets, as there is gravitational influence of the galactic tide and passing stars. We also compare the scattering process with and without migration of the giant planet.

We found Kuiper belt and Oort cloud like structures depending on the mass, orbit, and migration of the giant planet as well as on the mass of the central star and the initial distribution of planetesimals.

1. Introduction

Although it is still not yet clear, if the observed short term absorption variations in the profile lines are caused by analogues of comets, the theory is based on the knowledge about the Solar System. In the Solar System comets are remnants from the planet formation process, as there are asteroids. During the phase of planet formation these small objects have undergone gravitational scattering by the planets and been ejected to the outer rims of the Solar System onto highly eccentric orbits with huge values for semi-major axis. These objects reside in the Kuiper belt and the Oort cloud in the Solar System, occasionally disturbed by gravitational influence of the galactic tide or (probably in former times) the passing of a star which bring them close to the inner Solar System again. Close encounters with the giant planets can take care of exchange of angular momentum and lead to short periodic orbits with smaller resulting eccentricity.

2. The Model

The setup includes a Sun, a Jupiter-like planet and a disk of planetesimals (testparticles) distributed between 0.4 to 40 au. The testparticles have initially very small eccentricities ($0 \leq e \leq 0.1$) and inclinations ($0° < i < 2°$).

The integrations are performed with the *Mercury*-code.

We run computations with and without the influence of the galactic tide and passing stars.

Due to interaction of the Jupiter with the gaseous disk still present in the early planetary system the giant planet migrates and interacts gravitationally with the disk of planetesimals [1, 2].

Our computations include runs with and without migration of the giant planet in order to compare the scattering outcome.

As a consequence of the interaction of the giant planet with the planetesimals the small objects are scattered either inward or outward. The outward scattered objects will form analogues to the Kuiper belt respectively the Oort Cloud in our Solar System.

In order to apply the described method to extrasolar planetary systems we varied the mass of the central star and mass and orbit of the giant planet in reasonable ranges obtained from observations.

3. Summary and Conclusions

The created cometary reservoirs are different depending on the initial conditions of the integrated systems. Semi-major axis, eccentricity, perihel, aphel, inclination and orbital period after 2Gyr of integration of each testparticle are measured and statistics are made by comparing the outcomes of the computations with different acting forces. Additionally the influence of the migration of Jupiter on the outcome of the scattering process is examined by performing integrations with and without migration of the massive planet.

The gained knowledge can be used to generate a general model for the formation of cometary reservoirs in extrasolar systems with respect to the system architecture which can be used to predict the location of cometary reservoirs in extrasolar systems.

Acknowledgements

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Non-spherical dust dynamics in protoplanetary disks: the effects of particle nonsphericity on the evolution timescales

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Abstract

Recent high-resolution ALMA observations of protoplanetary disks [1] triggered interest in studying solid bodies in discs at different scales, ranging from small sub-micron grains up to solid bodies of sizes of hundreds of meters, for which the dynamical evolution is governed by the interaction with the gas in the disk.

For subsonic motion, the interaction with the gas causes a drag force acting on the dust particle that results in dust acceleration or deceleration. If the mean free path of the gas molecules is much larger than the size of the particles, the particles move in Epstein regime. In such regime, the difference in particle shape, size and composition lead to different aerodynamics and particle speeds.

Applying the non-spherical dust dynamics model developed for cometary environment [2], we study the dynamics of non-spherical particles in protoplanetary disks when the gas flow is in Epstein regime. In particular, we revise the timescales of the dimensionless stopping time ($t_{stop} = mv/F_{drag}$, with m and v being particle mass and velocity, F_{drag} the drag force) and the settling timescale in the vertical settling phenomena in disks.

We obtain the dust terminal velocities owing to the assumed shape/elongation and the region at which the settling could occur as a function of the particle non-sphericity. The results of this study have a direct application to the investigation of the effects of the unseen planetesimal population of protoplanetary disks to the evolution of their dusty environments [3].

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Pebble isolation and planetesimal formation by Super Earth planets

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Abstract

The constrains on the age and composition of the primordial bodies in the solar system require that the mixing stopped during the formation of Jupiter. The dust trap created by a 20 Earth mass embryo is proposed in several studies as an answer, but the timing is not fulfilled. Thanks to high-resolution simulations we show that a critical mass 3 times smaller is in fact sufficient, because the pebbles can stop inside the planet orbit. The growth towards Jupiter mass can be triggered by accretion of planetesimals, which form once the embryo is bigger than 20 Earth masses.

1. Introduction

The analysis of age, composition and isotope characteristic of primordial bodies of the solar system show that two distinct reservoirs exist within the protoplanetary disk. This dicotomy has appeared within less than 10^5 years, and is commonly explained by the formation of Jupiter. However, the stopping of the flux of solids requires a Jupiter core of 20 Earth masses (M_e) according to recent results ([3], [4]). The time needed to form such a core is still hardly compatible with the laboratory constrains. We present here a series of high resolution simulations where pebbles evolve in a disk containing a Jupiter embryo, to revisit this critical mass, and the effects on the distribution of pebbles in the disk.

2. Methods

We consider a 2D MMSN model of the disk, with background profiles of surface density and temperature in $\sigma_0(r) \propto (r/r_0)^{-1}$ and $T_0(r) \propto (r/r_0)^{-1/2}$, respectively. The reference radius is $r_0 = 5$ au. The gas has a cooling prescription in $[T - T_0(r)]/\tau_c$, with $\tau_c = 1000$ local periods, to allow dissipation of the heat generated by the shock waves. The pebbles are treated as a pressure-less fluid, fully coupled with the gas through the drag law proportional to the Stokes number $St = r_s \rho_s \sigma_g^{-1} \pi/2$. We use $St = 0.05$ at r_0, giving a radius of the pebbles r_s in the range $1.5-3$ cm depending on their composition ($\rho_s = 1-3\, g/cm^{-3}$). Gas and pebbles are evolved using the code RoSSBi ([1], [2]), which solves the Euler compressible equations on a polar grid using $(N_r,\ N_\theta) = (3072,\ 2048)$ cells for $1/3 < r < 2$ and $0 < \theta < 2\pi$. The planet orbit is evolved simultaneously, and migration is possible under the gravity exerted by the gas and the pebbles.

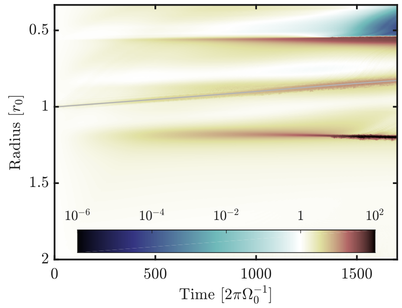
3. Stopping the flux of pebbles

3.1. Flux reduction in the inner disk

When the mass of the planet is in the range $8-10\, M_e$, the flux of pebbles is stopped for the inner parts of the disk. The left arm of the shock wave excited by the planet generates a trap, where the solids accumulate. The radial flux cancels, which avoids the pebbles to pass through and reach the inner parts of the disk. The location of this trap is around $r = 0.5\, r_0$ (see Fig. 1, top), and stays at this orbit for several thousands of disk orbits. The flux of pebbles from the outer parts of the disk is conserved, and the planet can keep growing by pebble accretion. This process has a strong impact on the explanation of the dicotomy in the composition of the meteoritic material and primordial bodies. The mixing through the disk can be stopped much earlier (few 10^5 years), because we show that the mass needed is $2-3$ times smaller than 20 M_e.

3.2. Flux reduction for the planet

When the planet grows to about 20 M_e, the pebble accretion onto the planet stops. The right arm of the shock carves the disk and generates a trap where the radial flux of solids reverses. This effect avoids the pebbles not only to reach the inner parts of the disk, but also the planet itself. The growth by accretion of solids stalls, which can explain the high probability to



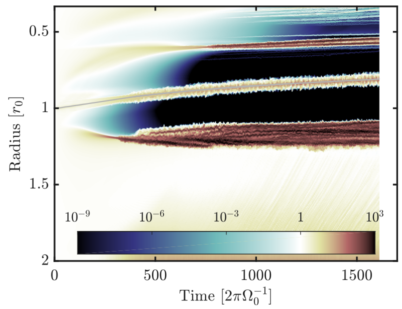


Figure 1: Time evolution of the pebble density for $M_p = 10\ M_e$ (top) and $M_p = 20\ M_e$ (bottom). The radial position of the planet is reported in gray line.

form Super Earth planets and to observe them in extra-solar systems. The location of this trap moves inward along the planet migration, which is still at work. Thus the region of accumulation of solids widen, in the region $1 < r < 1.2$ as seen of Fig. 1, bottom.

4. Planetesimal formation triggering

The accumulation of pebbles at the traps created by the planet creates a turbulent flow, where the formation of dust clumps is frequent (see Fig 2). These instable dust rings already observed in [1], contain several Earth masses in several solid-dominated eddies. This process is an alternative to the Streaming Instability to generate high dust-to-gas ratios in the disk, and is naturaly triggered by the planet whithin a short period of time, less than 5000 years. Under local gravitational instability, these clumps could form planetesimals and asteroids, which can decouple from the gas, and pass through the trap. The planet can then grow again by accretion of planetesimals, which is a recent promising senario to the formation of Jupiter.

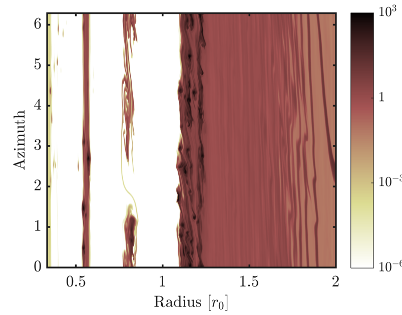


Figure 2: Pebble distribution in the disk after 1600 disk rotations (18×10^3 years) for a $M_p = 20\ M_e$ embryo.

5. Summary and Conclusions

The mass of the Jupiter embryo necessary to stop the mixing of solids with the inner solar system is in the range $8-10M_e$. The date of this stopping can be much earlier than previously estimated, and fall whithin the laboratory constrains. In this case, the trap is located between the planet and the star, which allows the core to keep growing. When it reaches the classical $20\ M_e$, pebble accretion on the embryo stops, but the possible planetesimal formation triggered on the outer parts can help entering a phase of planetesimal accretion, and form Jupiter.

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