FINAL REPORT OF K-OTKA 119993
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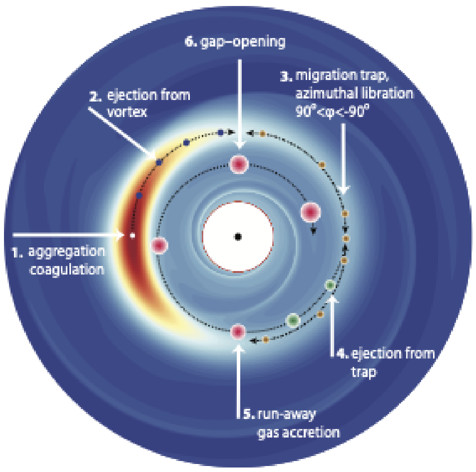
1 RESEARCH OBJECTIVES

TWO MAJOR THEORIES HAVE BEEN DEVELOPED to explain the formation of planetary systems. According to the *gravitational disc instability*, giant planets form via fragmentation and collapse of a massive disc due to its self-gravity Kuiper (1951); Cameron (1978). This process requires an effective cooling mechanism to ensure the formation of gravitationally bound gas clumps (Boss 2001, 2003). However, the high density and low temperature required are in contradiction with the majority of observations (Andrews & Williams 2005). Another process, the *core-accretion scenario* can explain the formation of both terrestrial and giant planets, starting with the formation of planetesimals via coagulation of dust particles (Safronov 1972). Collision of planetesimals leads to the formation of planetary embryos via the run-away and later the oligarchic growth (Wetherill & Stewart 1989; Kokubo & Ida 1998). By the subsequent collisions of the oligarchs, terrestrial planets form (Raymond et al. 2006). The formation of a giant planet starts with the buildup of a continuously accreting solid core. Reaching $15M_{\oplus}$, the core is massive enough to capture a gaseous envelope (Bodenheimer & Pollack 1986; Pollack et al. 1996). Despite the immense theoretical work, however, several problems of the core accretion scenario have not yet been solved.

FORMATION OF THE SOLAR SYSTEM aided by vortices has long been hypothesized. According to the first formulation of cosmogony given by *R. Descartes* in the middle of the XVIIth century and a hundred years later by *E. Swedenborg*, *E. Kant* and *P-S. Laplace*, inhomogeneities in the Universe contract and form the proto-Sun and a rotating flattened disc in which planets can form as a result of condensations. In the middle of the XXth century *C. F. von Weizsäcker* drafted a modern version of the formation of the Solar System. A common constituent of these cosmogonies is that the condensation process is driven by vortices. Indeed, vortices can play a crucial role in planet formation as pressure maxima developed in the vortex center can collect a large amount of solid material which helps to build up planetesimals and planetary embryos relatively fast (Barge & Sommeria 1995; Klahr & Henning 1997; Meheut et al. 2012b).

OUR RESEARCH addressed the unsolved problems of the current theory of planet formation by a modern concept of *planet formation in anticyclonic vortices*, see a representation in the figure on the right. This scenario can solve the problems related to the formation of planetesimals, e.g., too fast planetary migration, and too slow formation of the cores of giant planets. We investigated the dynamics of the early and late phases of protoplanetary discs. In the early phase, the dynamics are mainly perturbed by the disc instabilities and their self-gravity. Latter the newly born embedded planet can shape the disc, which continues to late phase in the debris discs. Predictions for planetary core growth were also given at the vicinity of pressure maximum developing inside vortices. The effect of the solid constituent of protoplanetary discs on terrestrial planet migration was revised for planets that are still accreting solid material. The stability of exoplanetary systems was thoroughly investigated. As an important part of the project a recently discovered, very compact exoplanetary system, TRAPPIST-1 was taken under extensive analysis.



Representation of different processes in the vortex-aided planet formation scenario.

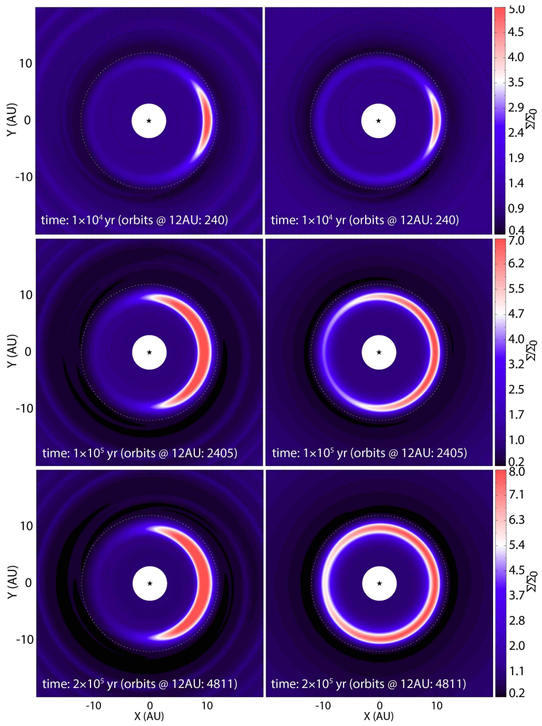
HYDRODYNAMICAL AND N-BODY SIMULATIONS were conducted to investigate the physical processes acting in planet formation. For numerical simulations, we used High-Performance Computing (HPC) clusters, as well as Graphical Processor Unit (GPU), aided computer architectures. Protoplanetary discs were modeled with GPU-based hydrodynamic code GFARGO, which was greatly improved by our group to handle the coupled dynamics of gas and dust as well as disc thermodynamics and self-gravity. The planet-disc interaction in debris discs, water delivery to planets in the late heavy bombardment process, and oligarchic planetary growth model were studied with our GPU-based N-body code, HIPERION developed during the research project.

2 Results

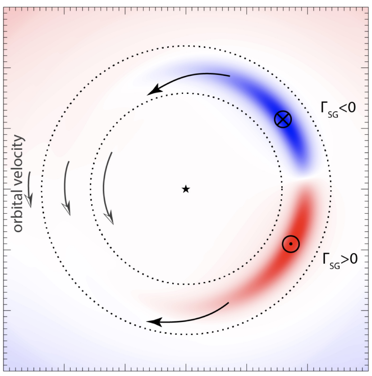
2.1 Formation and Evolution of Large Scale Vortices

Various physical processes that affect the formation of vortices were investigated, such as disc self-gravity, indirect potential, disc thermodynamics, and disc viscosity. We revealed the importance of the indirect potential appearing due to the cylindrical coordinate system used in hydrodynamic simulations. With the GPU implementation of disc self-gravity solver integrated into GFARGO, we revealed a new phenomenon called vortex stretching. A comparison study of large-scale vortex excitation in giant planet-bearing discs and viscosity transitions was performed. Disc thermodynamics was found to have a significant effect on vortex development. In a large parameter study, we determined an empirical disc mass limit for large-scale vortex formation. We also investigated the formation of large-scale vortices in dust dependent viscosity approximation model for the disc.

Grid-based hydrodynamics simulations of circumstellar discs are often performed in the curvilinear coordinate system, in which the center of the computational domain coincides with the motionless star. However, the center of mass may be shifted from the star due to the presence of any non-axisymmetric mass distribution. As a result, the system exerts a non-zero gravity force on the star, causing the star to move in response, which can in turn affect the evolution of the circumstellar disc. In Regály & Vorobyov (2017a), we studied the effects of stellar motion on the evolution of protostellar and protoplanetary discs. We adopted a non-inertial polar coordinate system centered on the star, in which the stellar motion was taken into account by calculating the indirect potential caused by the non-axisymmetric disc, a high-mass planet, or a large-scale vortex. We found that the stellar motion has a moderate effect on the evolutionary history and the mass accretion rate in protostellar discs and changing its inner shape from an initially axisymmetric to a non-axisymmetric configuration. Stellar motion slightly reduces the width of the gap opened by a high-mass planet, decreases the planet migration rate, and strengthens the large-scale vortices formed at the viscosity transition. An example of the effect of the indirect potential on the vortex formation is shown in the figures on the right. We concluded that the inclusion of the indirect potential is recommended in grid-based hydrodynamics simulations of circumstellar discs which use the curvilinear coordinate system.



Fully fledged vortex with (left panels) and without (right panels) indirect potential.

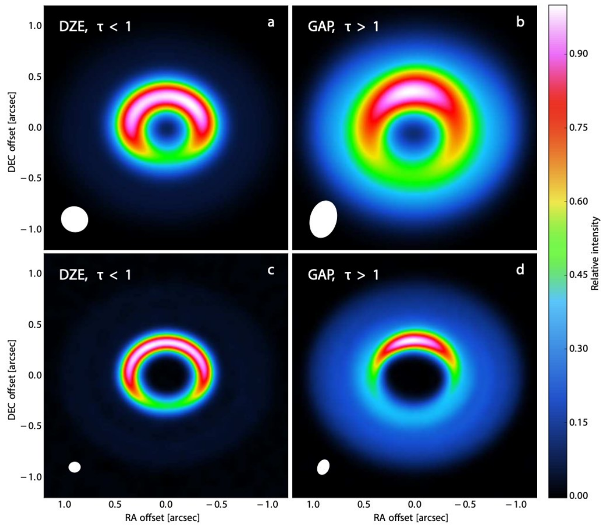


Vortex stretching disc torque.

Horseshoe-shaped brightness asymmetries of transitional discs are thought to be caused by large-scale vortices. Former studies suggested that the disc self-gravity weakens vortices formed at the edge of the gap opened by a massive planet in discs whose masses are in the range of $0.01 \leq M_{disc}/M_* \leq 0.1$. In Regály & Vorobyov (2017b), we investigated the long-term evolution of the large-scale vortices formed at the viscosity transition of the discs' dead zone outer edge utilizing 2D hydrodynamic simulations taking disc self-gravity into account. We performed a numerical study of low-mass, $0.001 \leq M_{disc}/M_* \leq 0.01$ discs, for which cases disc self-gravity was previously neglected. The large-scale vortices were found to be stretched due to disc self-gravity even for low-mass discs with $M_{disc}/M_* \geq 0.005$. As a result of stretching, the vortex aspect ratio increases. The strength of the vortex stretching is proportional to the disc mass. The vortex stretching can be explained by a combined action of a non-vanishing gravitational torque (see figure on the left) caused by the vortex and the Keplerian shear of the disc.

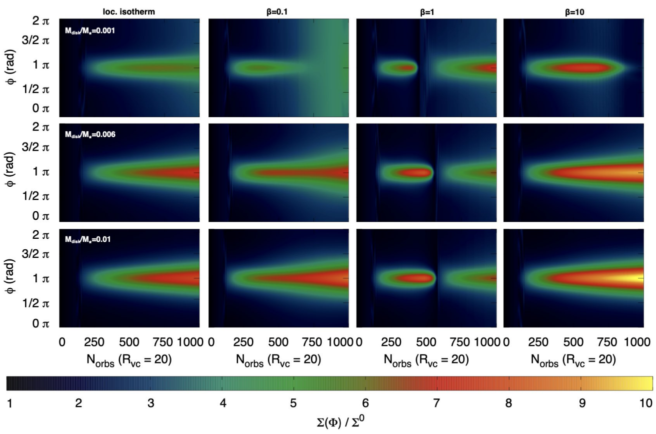
We gave observational predictions for the dust distribution affected by the vortex in the mm wavelengths by calculating synthetic ALMA images of vortices formed at the dead zone and planet-carved gap outer edges.

We also modeled the dust collection efficiency of pressure bumps in 1D model, taking into account dust growth. Non-axisymmetric brightness distributions are shown by recent mm-observations with a horseshoe-like morphology for several transition discs. The most accepted explanation for the observed asymmetries is the accumulation of dust in large-scale vortices. Vortices can form by the excitation of Rossby-wave instability in the vicinity of a steep pressure gradient, which can develop at the edges of a giant planet carved gap or at the edges of an accretionally inactive zone. In Regály et al. (2018), we studied the formation and evolution of vortices formed in these two distinct scenarios utilizing 2D locally isothermal hydrodynamic simulations. The gap-edge vortex was short-lived unless the disc is nearly inviscid. In contrast, the dead zone edge vortex was long-lived. The vortex morphology can be significantly different in the two scenarios: the vortex radial and azimuthal extensions are 1.5 and 3.5 times larger for the dead zone edge compared to gap models.



Synthetic ALMA images of large-scale vortex formed at dead zone edge (lef panels) and gap edge (right panels).

We calculate predictions for vortex observability in the mm-continuum, see figure on the right. Since the azimuthal and radial extent of the vortices, as well as the density contrast on the synthetic images, are different for the two scenarios we concluded that it is possible to infer the formation conditions of the vortices.

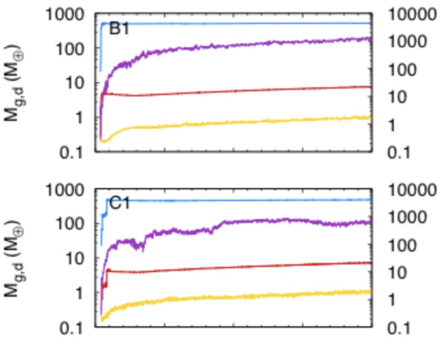


Vortex evolution in models using diffeent β–parameter.

EFFECT OF BETA-COOLING ON THE EVOLUTION OF VORTICES was investigated in Tarczay-Nehéz et al. (2020). Vortices were excited by Rossby Wave Instability, at the outer edge of the dead zone. We investigated three different disc mass models (including self-gravity), with five different beta-cooling parameters. We found that thermodynamics affects the onset time, mode number, strength, lifetime, and shape of the vortex. See examples of vortex evolution calculated by a series azimuthal density profile on the left figure. Including thermodynamics resulted in stronger, but decreased lifetime vortices. Our results showed that planet-formation can be enhanced in cooler discs, as in such discs vortices last longer.

AN EXTENSIVE PARAMETER STUDY ON VORTEX FORMATION was done in Tarczay-Nehéz et al. (2021) to explore the effect of disc geometry (the vertical thickness of the disc), viscosity, the width of the transition region at the dead zone edge, and the disc mass on the onset, lifetime, strength, and evolution of vortices formed in the disc. We performed a parametric study assuming different properties for the disc and the viscosity transition by running 1980 2D hydrodynamic simulations in the locally isothermal assumption with disc self-gravity included. Our results revealed that long-lived, large-scale vortex formation favors a shallow surface density slope and low- or moderate disc masses with Toomre $Q \lesssim 1/h$, where h is the geometric aspect ratio of the disc. In general, in low viscosity models, stronger vortices formed and rapid vortex decay and re-formation were observed in these discs.

VORTEX DEVELOPMENT AT SMOOTH VISCOSITY TRANSITION and subsequent development of large-scale vortex was studied in Regaly et al., in prep. RWI excitation requires a relatively sharp viscosity transition being in the order of the local pressure scale height. Thorough modeling of the physics of disc dead zone, however, revealed that viscosity transitions at the dead zone outer edge are relatively smooth. We presented 2D global non-isothermal gas-dust coupled hydrodynamic simulations to study a new possibility of vortex excitation at smooth viscosity transitions. In a parametric α viscosity prescription, the disc viscosity depends on the local dust-to-gas mass ratio.



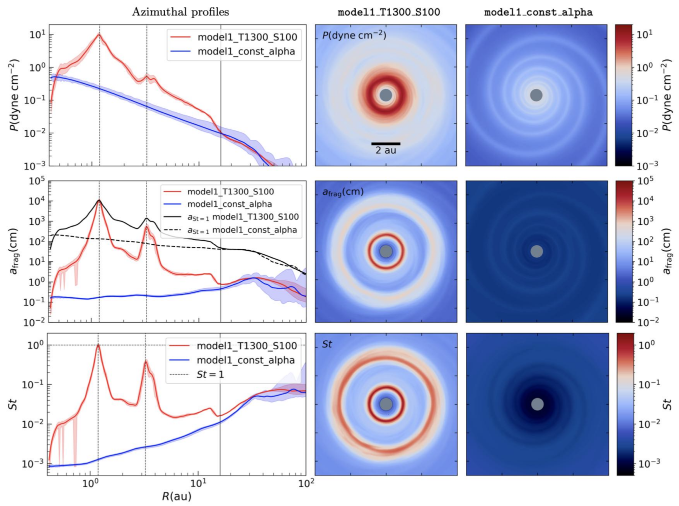
Gas and dust mass collected by vortices.

The parametric α model takes into account the effect of ion and free-electron recombination on the grain surfaces, which results in reduced disc viscosity. We found that disc dead zone outer edges where the viscosity transitions are smooth indeed can become Rossby unstable and form large-scale vortices in the parametric α prescription. Since the gaseous and dusty mass collected by these large-scale vortices can exceed 10-100 and 1-10 Earth masses, respectively, vortices provide ideal planet formation sites. The figure on the right shows gas (magenta) and dust (yellow) mass and dust-to-gas mass ratios (orange and yellow) as a function of time in two different models, where a large-scale vortex forms in parametric α model.

2.2 Early Evolution of Protoplanetarty Discs

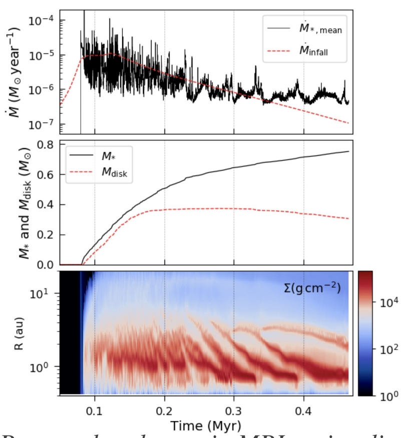
Formation and instabilities of young circumstellar discs strongly affect planet formation by resulting in discs that have various internal features such as rings and vortices. We investigated the early evolution of circumstellar discs with an advanced 2D hydrodynamic code that can model the formation of the circumstellar disc and handle stellar growth. Accretion outbursts driven by circumstellar disc physics around young stellar sources affect the stellar evolution (mainly stellar mass growth), which eventually determines the fate of planet formation.

Global simulations of protoplanetary disc formation and evolution were conducted in the thin-disc limit, where the model included a magnetically layered disc structure, a self-consistent treatment for the infall from cloud core, and the smallest possible inner computational boundary in Kadam et al. (2019). We compared the evolution of a layered disc with a fully magnetically active disc. With the canonical values of parameters a dead zone formed within the inner $\simeq 15$ au region of the magnetically layered disc. The dead zone was not a uniform structure, and long-lived, axisymmetric, gaseous rings ubiquitously formed within this region owing to the action of viscous torques, see an example of two simulations in the figure on the right. The rings showed a remarkable contrast in the disc environment as compared to a fully magnetically active disc and were characterized by high surface density and low effective viscosity. Multiple gaseous rings could form simultaneously in the dead zone region, which was highly dynamic and showed complex, time-dependent behavior such as inward migration, vortices, gravitational instability, and large-scale spiral waves. An increase in MRI triggering temperature had only marginal effects, while changes in active layer thickness and the initial cloud core mass had significant effects on the structure and evolution of the inner disc. Dust with a large fragmentation barrier could be trapped in the rings, which may play a key role in planet formation.



Gas pressure, dust fragmentation size and Stokes number distribution in two different global disc simulations.

Young stellar objects are undergoing sudden accretion events known as FUor or EXor outbursts. We conducted protoplanetary disc simulations in Kadam et al. (2020) assuming both magnetically layered and fully magnetorotational instability (MRI)-active disc structure. The instability in the dead zone in the disc resulted in MRI outbursts which results in sudden increase of stellar accretion rate, see an example of repeated outbursts in the figure on the left, where the highly variable stellar accretion rate, the mass evolution of the star and disc density profile evolution are shown. The simulations showed an instability analogous to classical thermal instability. The origin of unstable regions can be viewed as a novel mechanism behind short accretion events. We concluded that the magnetic structure of a disc, its composition, as well as the stellar mass, can significantly affect the nature of episodic accretion.



Repeated outbursts in MRI-active disc.

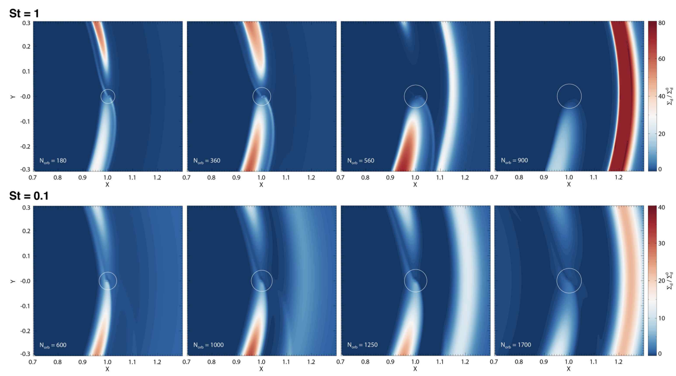
2.3 Modelling the Formation and Growth of Planets

Planet formation in the canonical theories faces difficulties due to the slow growth process. However, there is a new idea of accelerating planet formation in pressure maxima that for example can develop at the center of vortices. We investigated planetary growth in a 1D model that used an elaborated growth model as well as in 2D which can address non-axisymmetric effects. The oligarchic growth model was critically investigated by high-precision N-body simulations to reveal the possible side effects of artificial speed-up methods.

A simplified model of core accretion planet formation process was given in Kovács & Vanyó (2017). The leaky standard map allowed us to investigate the accretion rate onto a giant planet from a dynamic systems point of view. Besides the numerical tests, an elegant analytic solution to the problem has also been derived. The main result of our work explains how the particles escape from a certain region of the phase space and feed the forming planetary embryo. Nevertheless, our findings are more general and possible applications to other fields of physics can be relevant.

Planet formation in a pressure maximum of a protoplanetary disc was numerically studied in Guilera et al. (2020). The aim was to compute the radial drift of pebbles and planetesimals and planet migration at pressure maxima in a protoplanetary disc and their implications for the formation of massive cores as triggering a gaseous runaway accretion phase. The time evolution of a viscosity driven accretion disc was solved numerically introducing a dead zone as a low-viscosity region in the protoplanetary disc. A population of pebbles and planetesimals evolving by radial drift and accretion by the planets were also considered. Finally, the embryos embedded in the disc grown by the simultaneous accretion of pebbles, planetesimals, and the surrounding gas. Our simulations showed that the pressure maxima generated at the edges of the low-viscosity region of the disc act as planet migration traps, and that the pebble and planetesimal surface densities were significantly increased due to the radial drift towards pressure maxima locations. Our simulations also showed that migration-trap locations and solid-material-accumulation locations are not exactly at the same positions. Thus, a planet's semi-major axis oscillations around zero torque locations predicted by MHD and HD simulations are needed for the planet to accrete all the available material accumulated at the pressure maxima. Pressure maxima generated at the edges of a low-viscosity region of a protoplanetary disc seem to be preferential locations for the formation and trap of massive cores.

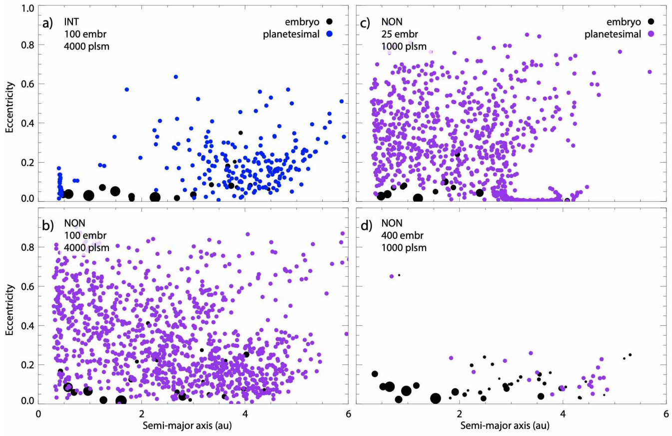
The growth of a pebble accreting planetary core was investigated in Sándor & Regály (2021) with 2D coupled dust-gas hydrodynamic simulations. Pebbles were treated as a pressureless fluid mutually coupled to the gas via drag force. We found that the core growth is stopped when reaching its isolation mass. A large number of pebbles $\sim 100 M_{Earth}$ should flow through the orbit of the core until reaching its isolation mass. The efficiency of pebble accretion is increased if the core grows in a dust trap of the protoplanetary disc. We identified four distinct phases of pebble accretion regimes, see figure on the right. Our results showed that in a global pressure maximum, the pebble isolation mass for a planetary core is significantly larger than in discs with power-law surface density profile.



Pebble surface density snapshots belonging to different phases of pebble accretion around the growing core for St=0.1 and 1.

To speed up simulations of planet formation via increasing the collision probability two ways are used generally: (i) confine motion to 2D, (ii) artificially enhance the physical radii of the bodies by an expansion factor. In Süli (2021), thorough analysis of 100 N-body simulations was presented. The main goal was to determine the probability distribution functions of the collision parameters and their dependence on the expansion factor. A simple method was devised to improve the determination of the collision parameters from the simulation data. It was shown that the distribution of the impact parameter is uniform and independent of the expansion factor. For real collisions, the impact velocity is greater than the mutual escape velocity. The results cast some doubts on simulations of the terrestrial planets' final accretion that have assumed merge. Collisional maps were created adopting the fragmentation model of recent studies to estimate the number of different types of collisions. A detailed comparison with earlier works indicated that there are similarities as well as significant differences between. The results indicated that the majority of collisions lead to mass growth either via partial accretion or via graze-and-merge collision as the planetary disc matures and the masses of the bodies differ progressively.

In the oligarchic growth model, protoplanets develop in the final stage of planet formation via collisions between planetesimals and planetary embryos. The majority of planetesimals are accreted by the embryos, while the remnant planetesimals acquire dynamically excited orbits. The efficiency of planet formation can be defined by the mass ratio between formed protoplanets and the initial mass of the embryo-planetesimal belt. In numerical simulations of the oligarchic growth, the gravitational interactions between planetesimals are usually neglected due to computational difficulties. In this way, computations require fewer resources. We investigated the effect of this simplification in Dencs & Regály (2021) by modeling the planet formation efficiency in a belt of embryos with self-interacting or non-self-interacting planetesimals. We used our own GPU-based direct N-body integrator for the simulations. We found that planet formation efficiency is higher if the planetesimal self-interaction is taken into account in models that contain the commonly used 100 embryos. The observed effect can be explained by the damping of planetesimal eccentricities by their self-gravity. The final number of protoplanets was independent of planetesimal self-gravity, while the average mass of the formed protoplanets was larger in the self-interacting models. We also found that the non-self-interacting and self-interacting models qualitatively give the same results above 200 embryos. Our findings showed that the higher the initial mass of the embryo-planetesimal belt, the higher the discrepancy between models that use self-interacting or non-self-interacting planetesimals is. The study of 3D models showed quantitatively the same results as the 2D models for low average inclination. We concluded that it is important to include planetesimal self-interaction in both 2D and 3D models in cases where the initial embryo number is less than 200.

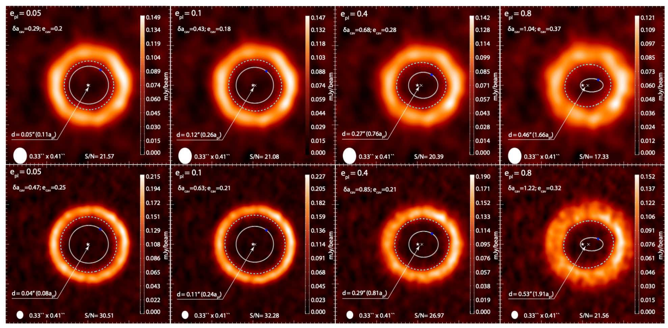


The eccentricity of embryos and planetesimals as a function of the semi-major axis in the oligarchic growth simulations assuming fully interacting (INT) and neglecting planetesimal self-gravity (NONINT).

2.4 Debris Disc, the Late Phase of Protoplanetary Disc Evolution

Debris discs are the remnant material of protoplanetary discs that are presumably underwent planet formation. Planets that are in the system can perturb the distribution of solid material orbiting the newly born star. This process was investigated as it can result in footprints, which can be used for observation to determine the mass and orbital parameters of unseen planets. A group of asteroids in our Solar System, the Hungaria family, can reveal such planet-asteroid interactions, whose spatial distribution was analysed. Debris discs are depleted in gas, however, several debris discs emit radiation in the near-infrared spectral range of CO molecule. By analysing the observations of such systems, we shed light on this contradiction.

Cavity observed in debris discs can be explained by the gravitational perturbation of an embedded giant planet. Planetesimals passing close to a massive body are dynamically stirred resulting in a cleared region known as the chaotic zone. The theory of overlapping mean-motion resonances predicts the width of this cavity. To test whether this cavity is identical to the chaotic zone, we investigated the formation of cavities utilizing collisionless N-body simulations assuming a 1.25-10 Jupiter mass planet with eccentricities of 0-0.9. Results were presented in Regály et al. (2018). Synthetic images at millimeter wavelengths were calculated to determine the cavity properties by fitting an ellipse to 14 percent contour level, see image on the right. Depending on the planetary eccentricity, e_{pl}, the elliptic cavity wall rotates as the planet orbits with the same ($e_{pl} < 0.2$) or half ($e_{pl} > 0.2$) period that of the planet. The cavity center is offset from the star along the semimajor axis of the planet with a distance of $d = 0.1q^{-0.17}e_{pl}^{0.5}$ in units of cavity size towards the planet's orbital apocentre, where q is the planet-to-star mass ratio. Pericentre (apocentre) glow develops for $e_{pl} < 0.05$ ($e_{pl} > 0.1$), while both are present for $0.05 \leq e_{pl} \leq 0.1$. Empirical



Synthetic ALMA images (assuming C43-5 antenna configuration) calculated for $q = 5 \times 10^{-3}$ and $e_{\rm pl} = 0.05, 0.1, 0.4$ and 0.8 models.

formulae were derived for the sizes of the cavities: $\delta a_{cav} = 2.35q^{0.36}$ and $\delta a_{cav} = 7.87q^{0.37}e_{pl}^{0.38}$ for $e_{pl} \leq 0.05$ and $e_{pl} > 0.05$, respectively. The cavity eccentricity, e_{cav}, equals to that of the planet only for $0.3 \leq e_{pl} \leq 0.6$. A new method based on Atacama Large Millimeter/submillimeter Array observations for estimating the orbital parameters and mass of the planet carving the cavity was also given.

A REGION AT THE INNER EDGE OF THE MAIN ASTEROID BELT is populated by the Hungaria asteroids. Among these objects, the Hungaria family is formed as the result of a catastrophic disruption of (434) Hungaria asteroid a hundred million years ago. Due to the Yarkovsky effect, the fragments depending on their direction of rotation are slowly drifting inward or outward from the actual place of collision. Due to this slow drift, these bodies could approach the locations of the various mean-motion resonances (MMRs) of outer type with Mars. We aimed to study the actual dynamical structure of Hungaria asteroids that is primarily shaped by various MMRs of outer type with Mars in Forgács-Dajka et al. (2021). We also searched connections between the orbital characteristics of Hungaria asteroids and their absolute magnitude. To map the resonant structure and dynamics of asteroids belonging to the Hungaria group, we used the method FAIR (as FAst Identification of mean motion Resonances), which can detect MMRs without the a priori knowledge of the critical argument. We also compiled stability maps of the regions around the MMRs by using the maximal variations in the asteroids' eccentricities, semi-major axes, and inclinations. We numerically integrated the orbits of all asteroids belonging to the Hungaria group available in the JPL Horizon database together with the Solar System planets for one and ten million years. Having studied the resonant structure of the Hungaria group, we found that several asteroids are involved in various MMRs with Mars. We identified both short and long-term MMRs. Besides, we also found a relationship between the absolute magnitude of asteroids and the MMR in which they are involved.

GAS-RICH PRIMORDIAL DISCS EVOLVE INTO GAS-POOR DEBRIS DISCS composed of second-generation dust. In Moór et al. (2017) we explored the transition between these phases by searching for 12CO, 13CO, and C18O emission in seven dust-rich debris discs around young A-type stars, using ALMA in Band 6. We discovered molecular gas in three debris discs. In all these discs, the 12CO line was optically thick. We compiled a volume-limited sample of dust-rich debris discs around young A-type stars within 150 pc. We obtained a CO detection rate of 11/16 above a 12CO J=2-1 line luminosity threshold of $1.4 \times 10^4 \mathrm{Jy\,km\,s}\,pc^2$ in the sample. This high incidence implies that the presence of CO gas in bright debris discs around young A-type stars is likely more the rule than the exception.

FOR TWO DEBRIS DISCS 49 CET AND HD 32297 we detected 13CO and C18O emission and measured very high CO masses of $> 0.01 M_{\mathrm{Earth}}$ using the ALMA 7m-array. These high CO contents imply a highly efficient shielding of CO against stellar and interstellar UV photons. In Moór et al. (2019), we explained the observed CO level in both systems by adapting a recent secondary gas disc model that considers both shielding by C atoms and self-shielding of CO. We found that the main stellar and disc properties are similar to those of previously identified CO-rich debris discs. These objects constitute the first known representatives of shielded debris discs.

2.5 DYNAMICS IN PLANETARY SYSTEMS

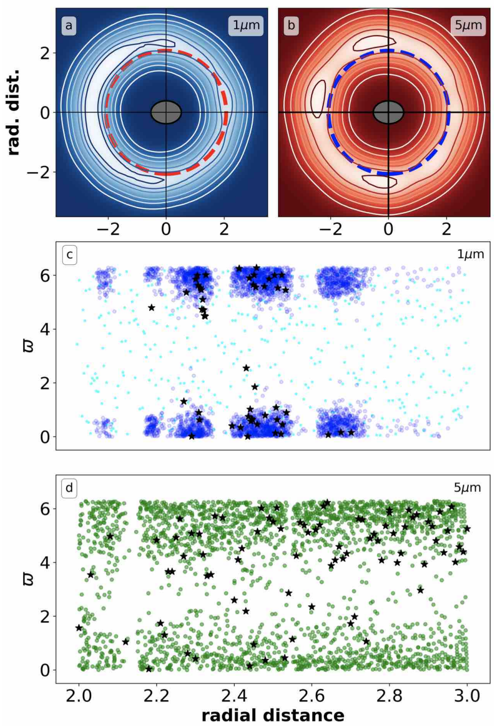
To study the history and final architecture of exoplanetary systems it is essential to solve the dynamical equations of the system, which is governed by gravitational forces. The dynamics of small bodies, however, are strongly affected by the radiation pressure of the star, which was investigated for a minor planet, Haumea and its ring system. Solutions to the dynamics of planetary systems can be derived by numerical N-body integrations, while the stability of multi-planet systems or minor bodies in the Solar System can be investigated theoretically too. Planets in some exoplanetary systems are arranged in a chain of mean-motion resonances, e.g., Kepler-60, whose long-term stability was investigated.

THE IDENTIFICATION OF MEAN MOTION RESONANCES in exoplanetary systems or the Solar system might be cumbersome when several planets and a large number of smaller bodies are to be considered. Based on the geometrical meaning of the resonance variable, an efficient method was introduced and described in Forgács-Dajka et al. (2018), by which mean motion resonances can be easily found without any a priori knowledge on them. The efficiency of this method was demonstrated by using known exoplanets engaged in mean-motion resonances, and also some members of different families of asteroids and Kuiper belt objects being in mean motion resonances with Jupiter and Neptune, respectively.

DUST DYNAMICS IN PROTOPLANETARY DISCS are affected by the stellar radiation pressure. We studied this effect in Kovács & Regály (2018) by modeling rings of minor planets. We showed that the particle dynamics, e.g., in Haumea's ring (a Trans-Neptunian dwarf planet) is dominated by outer spin-orbit resonances rather than the proposed inner 3:1 commensurability. We found that Solar radiation pressure plays an important role in dynamics: the eccentricity excitation caused by the radiation pressure and periapse alignment due to the asymmetric shape of the central body govern the ring dynamics together, see in the figure on the right.

SOLUTION TO A SPECIAL THREE-BODY PROBLEM, motion around triangular Lagrangian points was investigated in Boldizsár et al. (2021). The equations of motion of planar elliptic restricted three-body problem were transformed into four decoupled Hill's equations. By using the Floquet theorem analytic solution to the oscillator equations with time-dependent periodic coefficients were presented. It was shown that the new analytic approach is valid for moderate system parameters such as the eccentricity and mass parameter. We also clarified the transformation details that provide the applicability of the method and also demonstrated its applicability to extrasolar planetary systems.

THE TRANSPORT PHENOMENON AND ESCAPE RATE STATISTICS were studied in a 2D standard map presented in Lugosi & Kovács (2020). As a consequence of the leaks, the diffusion can be analyzed making use of only the ensemble of survived particles. The analysis of the escape direction also supports this picture as a significant amount of particles skip the leaks and leave the system just after a longtime excursion in the remote zones of the phase space. The application of this theoretical study to long-period comets might reveal the formation and the past of our solar system as well as extrasolar planetary systems.



Face-on view of the final stage of the integration (upper panels). The dashed line indicates the 3:1 spin-orbit resonance to Haumea. The gray ellipse represents Haumea to scale. The argument of pericentre for $1\mu m$ and $5\mu m$ shown on lower panels. Black stars are sampling the Haumea's ring for 1000 year integration.

AN APPLICATION OF THE SHANNON ENTROPY in the case of the planar (non-restricted) four-body problem was presented in Kővári et al. (2021). Specifically, the Kepler-60 extrasolar system was investigated with a primary interest in the resonant configuration of the planets that exhibit a chain of mean-motion commensurabilities with the ratios 5:4:3. In the dynamical maps provided, the Shannon entropy was utilized to explore the general structure of the phase space, while, based on the time evolution of the entropy, we determined also the extent and rate of the chaotic diffusion as well as the characteristic times of stability for the planets. Two cases were considered: (i) the pure Laplace resonance when the critical angles of the 2-body resonances circulate and that of the 3-body resonance librates; and (ii) the chain of two 2-body resonances when all the critical angles librate. Our results suggest that case (ii) is the more favorable configuration but we state too that, in either case, the relevant resonance plays an important role to stabilize the system. The derived stability times are no shorter than 10^8 yrs in the central parts of the resonances.

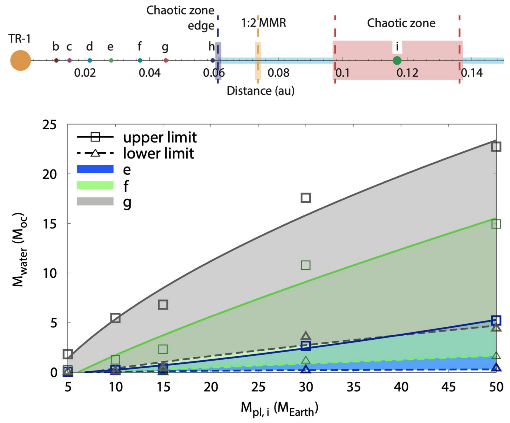
2.6 AN EXCEPTIONAL EXOPLANETARY SYSTEM, TRAPPIST-1

TRAPPIST-1 is an M8 type 0.0802 $M_\odot$ ultra-cool red dwarf star at a distance of 12.1pc from the Solar System harboring seven known Earth-sized rocky planets discovered by Gillon et al. (2017). By assuming that life requires liquid water, the search for extraterrestrial life is focused on Earth-like planets that can have liquid water on their surface. In a series of studies, we investigated the properties of TRAPPIST-1 system, such as interior structures, a possible LHB-like event, orbital resonances of planets, and the activity of the host star.

THE POSSIBLE INTERIOR STRUCTURES OF THE TRAPPIST-1 PLANETS were mapped, and calculated their tidal heating and the total incident radiation in Brasser et al. (2019). We showed that TRAPPIST-1d and e can avoid a runaway greenhouse state. Planet e is the most likely to support a habitable environment. Planet d also avoids a runaway greenhouse, if its surface reflectance is at least as high as that of the Earth. Planets b and c have heat fluxes high enough to trigger a runaway greenhouse and to support volcanism on the surfaces rendering them too warm for life. Planets f, g, and h are too far from the star to experience significant tidal heating, and likely have solid ice surfaces with possible subsurface liquid water oceans.

The resonances between the TRAPPIST-1 planets and their long term stabilities were investigated in Dobos et al. (2019). The aim of the research was to constrain the dissipation factor of the planets obtained both from orbital dynamic calculations and from their interior structures. The dynamical simulations showed that the planets typically go unstable 30 Myr after their formation. The agreement between the dynamical and interior models is not too strong, but is still useful to constrain the dynamical history of the system.

Three of the seven rocky planets in TRAPPIST-1 system orbit in the habitable zone of the host star. Therefore, water can be in liquid state at their surface being essential for life. Water frozen in the building blocks of planets can be lost due to their frequent collisions during planet formation. However, a potential subsequent water delivery event, like the late heavy bombardment in the Solar System, can replenish planetary water reservoirs. We investigated this water delivery process in Dencs & Regály (2019). We created a simple model in which an additional planet is embedded in a water-rich asteroid belt. Asteroids perturbed out from the chaotic zone of the putative planet can enter into the inner system and accreted by the known planets. We found that the farther the planet orbits from the star, the higher is the amount of water delivered to them, see figure on the right. Our results are applicable to the Solar System to get more accurate estimations for the meteoritic impact numbers of rocky planets than the currently accepted crater density value.



Schematic view of the TRAPPIST-1 system with a putative water-rich outer disc and giant perturber (upper panel). Water delivery predictions in the numerical simulations (lower panel).

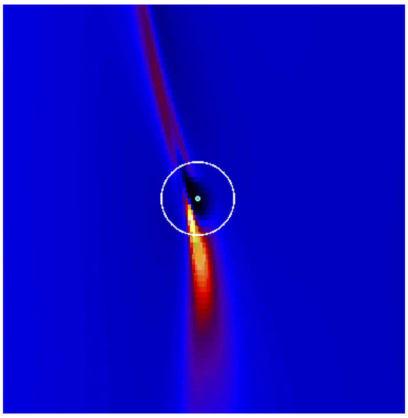
In a review article by Dehant et al. (2019), we discussed the geophysics and habitability of bodies both in the Solar System and beyond. We addressed how interactions between the interior of a planet or a moon and its atmosphere and surface can affect habitability of the celestial body. We focused on surface conditions capable of sustaining life and deal with fundamental issues of planetary habitability. We addressed the identification of preserved life tracers in the context of the interaction of life with planetary evolution.

Understanding the magnetic activity and the implications for habitability of ultracool dwarf stars is of prime importance as more exoplanets are being discovered around them. In Seli et al. (2021), an analysis was presented on TRAPPIST-1 analog ultracool dwarfs with TESS full-frame image photometry from the first two years of the primary mission. A volume-limited sample up to 50 pc is constructed consisting of 339 stars closer than 0. m5 to TRAPPIST-1 on the Gaia color-magnitude diagram. We analyzed the 30 min cadence TESS light curves of 248 stars, searching for flares and rotational modulation caused by starspots. The composite flare frequency distribution of the 94 identified flares shows a power-law index that is similar to TRAPPIST-1 and contains flares up to ETESS $= 3 \times 10^{33}$ erg. Rotational periods shorter than 5d were determined for 42 stars, sampling the regime of fast rotators. The ages of 88 stars from the sample were estimated using kinematic information. A weak correlation between rotational period and age is observed, which is consistent with magnetic braking.

2.7 Novel Methods and New Phenomena Discovered

Finally, we highlight three major results of our research project. The long-term stability of the planetary system is crucial for the development of life on their surfaces. The commonly applied method was to compute long–term N-body simulations to reveal the stability of observed exoplanetary systems. In the confines of our project, however, a fast method was developed based on the analysis of non-linear time series. Two new phenomena that can play a crucial role in planet formation and the evolution of planetary systems were discovered by our group. We described a possible phenomenon that can alleviate the problem of the fast inward migration of terrestrial planets. With the help of numerical hydrodynamic simulations, we identified a new disc instability process that results in vortex cascade generation.

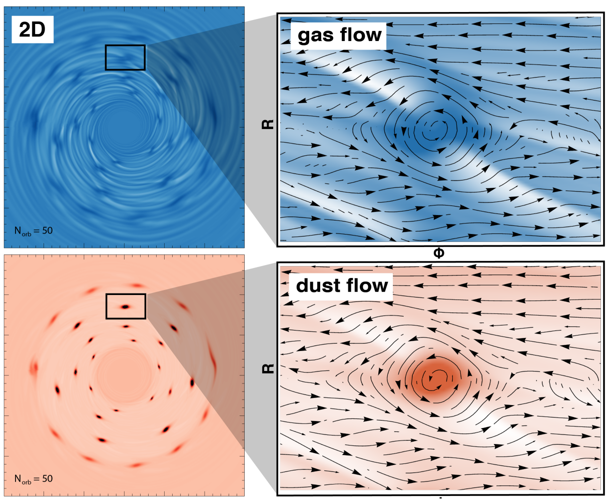
A novel method applied to extrasolar planetary dynamics was proposed in Kovács (2020) to describe the system stability. The observations in this field serve the measurements mainly of radial velocity, transit time, and/or celestial position. These scalar time series are used to build up the high-dimensional phase space trajectory representing the dynamical evolution of planetary motion. The framework of non-linear time series analysis and Poincaré recurrences allowed us to transform the obtained univariate signals into complex networks whose topology carries the dynamical properties of the underlying system. The network-based analysis is able to distinguish the regular and chaotic behaviour not only for synthetic inputs but also for noisy and irregularly sampled real world observations. The proposed scheme does not require neither N-body integration nor best-fitting planetary model to perform the stability investigation therefore the computation time can be reduced drastically compared to those of the standard numerical methods.



Strongly asymmetric distribution of solid matter around the planet.

SOLID MATERIAL – DUST, PEBBLES, PLANETESIMALS although constitutes only 1% of mass in protoplanetary discs, it can have a major consequence on planetary migration. Benítez-Llambay & Pessah (2018) have shown that the highly asymmetric distribution of pebbles in the vicinity of a planet formed due to planet-disc interactions can also exert significant torque on the planet. Depending on the size of particles and planetary mass the solid torque is positive and its amplitude overcomes that of gas. In Regály (2020), we presented that accretion of solids can strengthen this effect by increasing the spatial asymmetry of dust distribution, see the image on the left showing the distribution of solid material in the vicinity of the accreting planet. As a consequence, a torque reversal can occur, which results in the outward migration of planets. This study revealed that the migration of solid accreting planets can be substantially departed from the canonical analytical type-I prediction.

VORTEX CASCADE as a self-sustaining planet formation process was recently discovered in Regály et al. (2021). We found a new phenomenon in 2D hydrodynamical simulations that leads to continuous generation of small-scale vortices (see figures on the right). The vortex self-replication is initiated by a plausible assumption that the local value of the effective disc viscosity depends on the local dust-to-gas mass ratio (Dullemond & Penzlin 2018). The vortices are secularly stable due to the positive feedback loop and are subject to complex interactions such as mergers and orbital decay. An individual vortex could collect a significant amount of dust (about $10M_{\oplus}$). As traditional barriers to dust growth and planetesimal formation can be overcome due to the suitable local conditions as well as vortex stability over a large number of orbits, self-sustaining vortices sets a favorable stage for the planet formation.



Vortex cascade in the parametric α viscosity model.

3 EXPEDIENCE

GPU-BASED CODES IMPLEMENTED BY OUR GROUP have been greatly contributed the success of our K–OTKA 119993 grant. Due to the large computational demands of long-term (Myr time-scale) global hydrodynamic simulations, we used codes that specifically developed for Graphic Processing Unit (GPU) accelerated hardware. For the hydrodynamic simulations, we improved the GPU-based code GFARGO (an GPU version of FARGO, a fast advection method developed for studying planet-disc interactions, Masset 2000). For N-body simulations, the GPU-based code developed by our group, HIPERION was used.

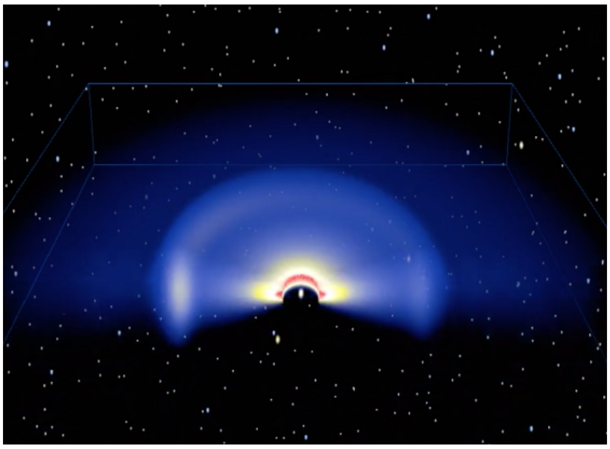
THE GPU-BASED HYDRODYNAMIC SOLVER, GFARGO2 is now capable to model both the gas and dust (as a pressureless Eulerian fluid), disc self-gravity (both gas and dust), disc thermodynamics, and planetary accretion. Based on our recent study (Regály 2020), to reach numerical convergence in dust dynamics, a high numerical resolution is required – the number of grid cells required was 1.5K×3K instead of conventional 0.5K×1K. To alleviate the resolution demand an adaptive mesh refinement method was developed. Dust growth was also implemented in

GFARGO2 according to the method described in Vorobyov et al. (2018) and Benítez-Llambay et al. (2019).

THE GPU-BASED N-BODY INTEGRATOR, HIPERION was used for modeling the gravitational interaction of N-body system. Interactions of a large number of planetesimals (up to a million), planetary embryos (up to a thousand), and several planets can be calculated with HIPERION, which utilizes 4th, 6th, and 8th order Hermite scheme with adaptive time-step (Nitadori & Makino 2008). HIPERION code was successfully used in several investigations that required direct integration of large number of gravitational objects.

VIRTUALIZATION OF HIGH-PERFORMANCE GPU-ENABLED COMPUTING ARCHITECTURE (VHP–GPU) was generally used in our research project. We set up a DOCKER based platform on our GPU servers using OS-level virtualization to deliver softwares in packages called containers. We invented a solution that provides real-time GPU-rendering through docker containers. With this unique solution, researchers were able to run and analyze the results of simulations on the fly. Our VHP–GPU architecture contributed to the success of our and several other research projects such as Marton et al. (2019); Pritchard et al. (2021); Nagy et al. (2021).

PASSIVE STEREOSCOPIC 3D PROJECTION SYSTEMS operating in Konkoly Observatory[1] was assisted by our group for scientific dissemination. Computer rendering of 3D anaglyph or side-by-side images and animations requires extensive computations. For this purpose, we used a dedicated free software BLENDER Renderer that ran on NVIDIA 2080 GPU-accelerated server financed by our research project. With computer rendering, scientific results can be displayed in virtual 3D. Human brain percepts the 3D depth with binocular vision via stereopsis: objects at different distances projected to the fovea such the angular distance of the images of the objects is different in the two eyes. As a result, we are capable of percept the depth of space. We developed a technique to present our 3D numerical simulations in virtual 3D space, see an illustration on the right showing a cross-section of a disc that harbours a large-scale vortex. Our development of virtual 3D projection technique greatly contributed to the success of furbishing the more than 100 years old stereoscopic photographs taken by Loránd Eötvös. The digital versions of Eötvös's stereoscopic phtotographs[2] were presented in the ceremony of 100th anniversary of the death of Lorand Eötvös held at MTA.



Computer rendered virtual 3D cross-section of a large-scale vortex from hydrodynamic simulation.

4 SUMMARY AND CONCLUDING REMARKS

VORTEX-AIDED PLANET FORMATION AS A PROMISING NOVEL HYPOTHESIS was studied extensively in our research project utilizing numerical hydrodynamics and N-body simulations on a GPU-supported HPC system. The scientific results were published in 34 refereed Q1 journals and 5 additional are soon to be published. Our result were also presented as talks and posters in international conferences such as *Missing links from disks to planets*, Konkoly/MPIA workshop 2016; *The disc migration issue: from protoplanets to supermassive black holes*, Cambridge 2017; *Planet Formation and Evolution*, Jena 2017; *Numerical Simulations of Planet-Disc Interactions*, Cuernavaca 2017; *General Assembly of the International Astronomical Union*, Vienna 2018; *Planet Formation and Evolution*, Rostock 2019. We also publish 3 scientific dissemination articles for the general audience in Fizikai Szemle.

TO SUMMARY, we found that large-scale vortices can develop for a wide range of properties in protoplanetary discs and their formation mechanism can be derived by observations. Vortex formation is significantly affected by the physics that govern the evolution of protoplanetary discs. Vortices can appear at early phases of protoplanetary discs as well as later epochs in transitional discs. Planetary growth inside pressure maximum developing at the center of the vortex is significantly accelerated. We concluded that vortex-aided planet formation is favored in relatively low mass and fast cooling disc. Regarding modeling the assembly and late dynamics of planetary systems,

[1] See more details and freely available 3D movies at https://konkoly.hu/staff/regaly/grants/3dnal.html

[2] Digital version of stereograms can be found at the following address: https://eotvos100.hu/en/page/tomorlatvany_kepek

we thoroughly tested the known models. We proposed better handling of interactions in such simulations and suggested a new method to use for investigations of planetary system stability. A newly discovered out-of-the-common exoplanetary system, TRAPPIST-1, was taken under extensive investigation to reveal important aspects of planet formation. Studies on the late phase of protoplanetary disc evolution led us to develop a new model for the formation of disc structures such as inner holes of debris discs and identified new debris discs that still contain a significant amount of gas. The surprising phenomenon found, i.e., the outward migration of accreting plants caused by the solid component of protoplanetary discs raises a possible solution to the long-standing fast inward planetary migration problem. Our novel discovery of the vortex cascade phenomenon in the parametric α viscosity model raises a completely new hypothesis of planet formation, which is worth investigating extensively in the near future.

OUR TEAM CONSISTED OF HUNGARY'S EXPERT SCIENTISTS on the field of planet formation. The research project used a strong collaboration between Konkoly Observatory and Eötvös Loránd University. Team members were affiliated at Konkoly Observatory, the Department of Astronomy, and the Department of Theoretical Physics at the Eötvös Loránd University. Senior project members were experts in various fields of astrophysics, such as physics of planet-disc interactions, the evolution of protoplanetary discs, the habitability of exoplanets, dynamics of planetary systems including N-body simulations. We also extended our collaborations with internationally renowned groups and scientists such as E. Vorobyov (University of Vienna), O. M. Guilera (National University of La Plata, Argentina), W. Kley (University of Tübingen), C. P. Dullemond (University of Heidelberg), and D. Semenov (Max-Planck Institute of Astronomy). Two Ph.D. students involved in the proposed research have successfully finished their thesis and got their degree (Zoltán Dencs) and will defend their thesis soon in 2021 (Dóra Tarczay-Nehéz). The project also supported one MSC (Máté Szilágyi), three BSC (Máté Szilágyi, Balázs Tószegi, Gergely Krupándzky) degrees, and three (Kristóf Rozgonyi, Balázs Tűszegi, Gergely Krupánszky) OTDK nominees.

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