RESEARCH PLAN FOR K-OTKA 119993

NEW DIRECTIONS IN UNDERSTANDING PLANET FORMATION

VORTEX-AIDED PLANET FORMATION

1 PLANET FORMATION - IN THE FOREFRONT OF ASTRONOMY TODAY

PLANET FORMATION STUDIES are at an exponential exploratory phase. As of today, more than 2000 exoplanets have been discovered and there could be as many as 40 billion Earth-sized planets orbiting in the habitable zones of Sun-like stars and red dwarfs within the Milky Way (Petigura et al. 2013). Observations reveal planets showing astonishing diversity: terrestrial rocky planets, gas giants with even 10 Jupiter masses orbiting in close vicinity, or at farther distances from their host star. One of the fundamental missions of the modern astronomy is to understand how these planetary systems formed and why their architectures are so different from that of the Solar System.

PROTOPLANETARY DISCS, the remnants of the star forming nebulae, are believed to be the birth places of planetary systems. Due to the remarkable development of astronomical instruments in the past decade it became possible by now to spatially resolve these discs and study them with unprecedented details. Thus, theoretical description of planet formation needs to be such level where it can directly been tested by the observations.

1.1 CANONICAL THEORIES OF PLANET FORMATION AND THEIR PROBLEMS

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). An other 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). However, despite the immense theoretical work several problems of the core accretion scenario have been revealed.

THE METER-SIZE BARRIER states that solid bodies in discs cannot grow beyond a critical size of about a meter. As growing dust grains dynamically decouple from the gas, an aerodynamic drag force arises resulting in a fast inward drift of dust particles. The radial drift velocity has a maximum for particles in the meter size regime at 1AU. In the absence of any retaining mechanisms, meter-sized pebles quickly fall into the star (Weidenschilling 1980).

SEVERAL OTHER BARRIERS can prohibit the formation of planetary embryos. Due to the size-dependent radial velocities, dust aggregates of different sizes collide with high velocities, resulting in fragmentation and erosion instead of further growth (Weidenschilling & Cuzzi 1993). Bouncing of dust aggregates can stop the collisional growth of dust particles already before the fragmentation barrier at about particle sizes of chondrules (Zsom et al. 2010). The combination of electric repulsion and collisional fragmentation between colliding aggregates also impose a serious limitation on growth of dust particles to pebles (Okuzumi 2009).

THE TIMESCALE PROBLEM OF GIANT PLANET FORMATION emerges due to the limited lifetime ($\sim$ 5Myr) of gaseous protoplanetary discs (Haisch et al. 2001). Giant planets requires the solid planetary core to capture an envelope via runaway gas accretion (Pollack et al. 1996), which may take longer time than the disappearance of gas. This time can be shortened by the replenishment of the planetary feeding zone via migration, however, this requires an artificial (about an order of magnitude) reduction of the migration rate (Alibert et al. 2004, 2005)

FAST INWARD MIGRATION OF PLANETS is another problem. Low-mass planets (several $M_\oplus$) induce $m = 2$ mode spiral waves in the disc. Due to the imbalance of torques exerted by these spiral waves, low-mass planets are subject to fast Type I inward migration. The orbital distance decreases at such a rate that the planet is engulfed by the star before the disc disperses (Ward 1997; Tanaka et al. 2002). Angular momentum exchange between a massive planet (above the mass of Saturn) and the disc leads to the opening of a density gap along the planetary orbit. Therefore the migration of high-mass planets (Type II regime) is no longer affected by the spiral waves, but its time-scale depends on the disc's viscosity, which is typically shorter than the mean disc life-time (Lin & Papaloizou 1986).

1.2 Former extensions to the classical planet formation theory

Due to the above mentioned problems – some of which are several decades old – the classical model(s) of planet formation had to be extended. The most important aspect of the extension of the classical theory was to solve all the problems locally in the disc instead of finding a solution for the whole disc.

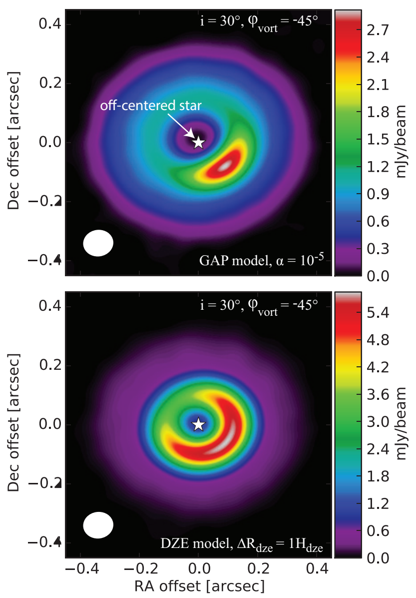
Large-scale anticyclonic vortex can develop in protoplanetary discs due to the excitation of Rossby wave instability (RWI). It is widely accepted that angular momentum transport and accretion is driven by the turbulent viscosity provided by the magneto-rotational instability, which requires the interaction of ionised plasma with the stellar magnetic field (Balbus & Hawley 1991). At high column densities, the gas is self-shielded against ionising radiation, thus a non-ionised region, the so-called *dead zone* develops, where the turbulence and the disc's viscosity are strongly suppressed (Gammie 1996). Due to a steep viscosity transition at the dead zone boundaries RWI can be excited leading to the formation of a large-scale anticyclonic vortex (Lovelace et al. 1999; Li et al. 2000, 2001). Vortices can also develop near the steep density gradient of giant planet opened gap edges (Li et al. 2005), however, they disperse within several hundred orbits for canonical disc viscosity (de Val-Borro et al. 2007).

Large amount of dust can be collected at the pressure maximum developed in the vortex centre (Barge & Sommeria 1995; Klahr & Henning 1997). As a result, planetesimal formation can be accelerated there (Meheut et al. 2012b). Later vortices may collapse and become gravitationally bound clumps forming planetary embryos (Lyra et al. 2009a). If produced with sufficient frequency, planetary embryos undergo further collisions resulting in rapid formation of a several Earth mass core (Sándor et al. 2011).

The concept of planetary migration trap has been first described by Masset et al. (2006b) demonstrating that a steep density jump can halt the migration of low-mass planets. Indirect evidence of the planet trap has been found based on that the distribution of the semi-major axes of the observed exoplanets is consistent with slowed migration (Schlaufman et al. 2009). However, Morbidelli et al. (2008) found that several low-mass planets embedded in a planet trap bearing gaseous disc form a non-migrating configuration.

Reduced, halted or even reversed Type I migration can occur in discs with very shallow density profile or assuming a non-isothermal, adiabatic equation of state for the gas due to the positive corotation torque exerted on the planet by the gas (Masset et al. 2006a; Paardekooper & Mellema 2006; Kley & Crida 2008). This mechanism can save low-mass planets from the deadly engulfment and explain exoplanets observed on wide orbits.

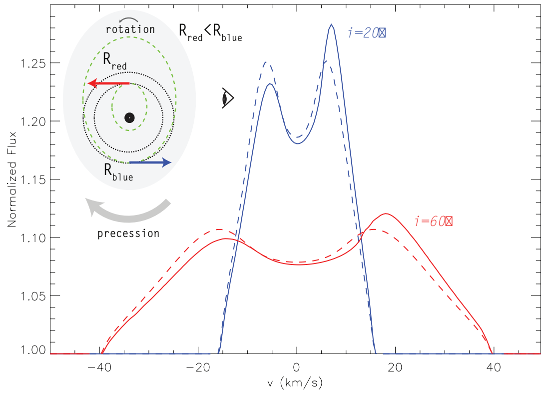
1.3 Recent developments and the PI's contribution



Several transitional discs, which represent an advanced phase of protoplanetary disks evolution, show non-axisymmetric brightness distribution in the sub-millimetre wavelengths (e.g., Brown et al. 2009; Andrews et al. 2011; Casassus et al. 2013; van der Marel et al. 2013). These asymmetries can be explained by the development of a large-scale vortex at the outer edge of the disc's dead zone as was shown in **Regály, Zs.** et al. (2012). Transitional discs show dust clearing at their inner regions too, which can also be explained by the same model as the dead zone edges are very efficient in collecting millimetre-sized dust particles. It is still an open question whether these brightness asymmetries are caused by a short-lived ($\sim$ 10 Kyrs) vortex developed at the gap edge of multiple giant planets (Dodson-Robinson & Salyk 2011; Zhu et al. 2011) or a long-lived vortex formed at the viscosity transition. According to the PI's recent study, the morphology of the brightness distribution can be used to infer the origin of the vortex (see images to the left). While the gap edge vortex has high contrast and is azimuthally compact (upper panel), the dead zone edge vortex has low contrast and is azimuthally extended (lower panel) (Regály, et al. 2016, submitted to ApJ) similarly to the majority of observations.

Anticyclonic vortices act as planetary traps due to the development of pressure maximum at their centres, but based on the PI's studies, they serve as temporary traps only for low-mass planets (**Regály, Zs.** et al. 2013; Ataiee et al. 2014). A low-mass planet can be trapped in an overdense region close to the vortex, where they can grow faster than in the classical core-accretion scenario. However, the low-mass planets are ejected from the trap after about a hundred thousand years. In conclusion, the large-scale vortices formed at viscosity transitions are promising places of persistent planet formation. This finding, together with the efficient dust accumulation in vortices, suggests a promising new scenario for planet formation, the so-called *vortex-aided planet formation scenario*.

MASSIVE PLANET EMBEDDED IN A DISC gravitationally perturbs the gas flow forcing the gas parcels to eccentric orbits in the vicinity of the planetary orbit (Kley & Dirksen 2006). According to an earlier study of the PI, such local disc eccentricity can be observed as a distortion of the double-peaked emission lines of the CO molecule in its fundamental band ($4.7\,\mu$m) spectrum, if the planetary orbit is inside the CO thermal excitation zone (**Regály, Zs.** et al. 2010). These emission lines are found to show periodic changes in their shapes as the planet orbits the star. The PI also found that CO lines emitted by the circumprimary disc of a close-separation binary system is clearly asymmetric (see the figure to the right) due to the global disc eccentricity excitation (**Regály, Zs.** et al. 2011a,b). Recently, the PI has shown that the disc becomes not only locally but globally eccentric in the long run due to the perturbation of a giant planet (**Regály, Zs.** et al. 2014). In summary, it is possible to infer the presence of a giant planet orbiting closer than about 15 AU still surrounded by gaseous disc (which are thereby hidden for direct imaging) by high-resolution near-IR spectroscopic monitoring of the CO-emission. Note that hints of such line asymmetries have already been observed (see e.g., Pontoppidan et al. 2008; Brown et al. 2013; Goto et al. 2011)



LARGE-SCALE VORTEX FORMATION AND SURVIVAL in dead zone bearing discs require further investigation, as special conditions must exist in the disc to excite RWI and support long-lived vortices. In α-discs (Shakura & Sunyaev 1973), the excitation of RWI is thought to occur at sharp viscosity transitions (Lyra et al. 2009b; **Regály, Zs.** et al. 2012). However, detailed simulations of the formation of the dead zone suggest a smooth viscosity transition (Dzyurkevich et al. 2013). Interestingly, MHD simulations by Lyra et al. (2015) showed that vortices can form even if the viscosity transition is smooth.

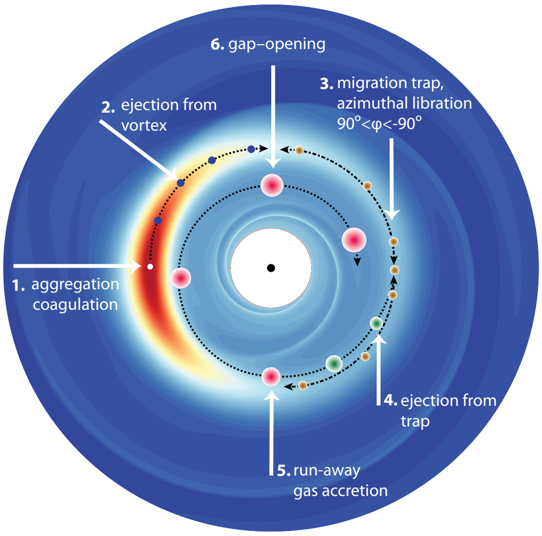
REGARDING THE EVOLUTION OF VORTICES FORMED AT PLANETARY GAP EDGES several new phenomena have been revealed recently. Vortices found to have 3D structures, however, their formation can be modelled well in 2D (Meheut et al. 2012a). The dust feed-back effect can destroy the gap edge vortices if the gas-to-dust mass ratio exceeds unity at their centre (Fu et al. 2014). In locally non-isothermal discs, the life-time of vortices are found to be shortened with increasing cooling time (Les & Lin 2015). The PI's former investigations assumed local isothermal and non-self-gravitating discs, thus although the above findings are related to the evolution of gap edge vortices, it is important to incorporate the thermal, self-gravity, and 3D effects for dead zone edge vortex evolution.

2 MAIN RESEARCH OBJECTIVES

ONE OF THE HOTTEST TOPICS and the fastest developing field of astronomy is planet formation. An immense theoretical and observational effort is being undertaken to solve the previously described open questions and to better understand how planets form. The goal of the proposed research is to investigate the plausibility of a fast *vortex-aided planet formation* scenario that can tackle some of the most serious problems of the currently accepted planet formation paradigm, the core accretion theory.

2.1 VORTEX-AIDED PLANET FORMATION HYPOTHESIS

THE PROPOSED PLANET FORMATION SCENARIO can be summarised as follows (depicted on the next page): (1) Initially, a significant amount of gas and small-sized dust are accumulated by a large-scale vortex developed at the viscosity transition of the outer edge of the disc's dead zone. (2) Due to the low turbulence in the dead zone, dust aggregates can reach cm to dm sizes and grow even further by sweeping up the small particles. Together with the dust collecting property of vortices (Johansen et al. 2007) the *drift, fragmentation, and bouncing barriers* might be overcome resulting in the formation of planetary embryos. (3) Leaving the vortex centre, the planetary embryo enters a migration trap at an overdense region, where it can quickly grow by planetesimal accretion or by collisions with already formed embryos, *solving the slow growth of planetary core and the fast Type I migration problem.*

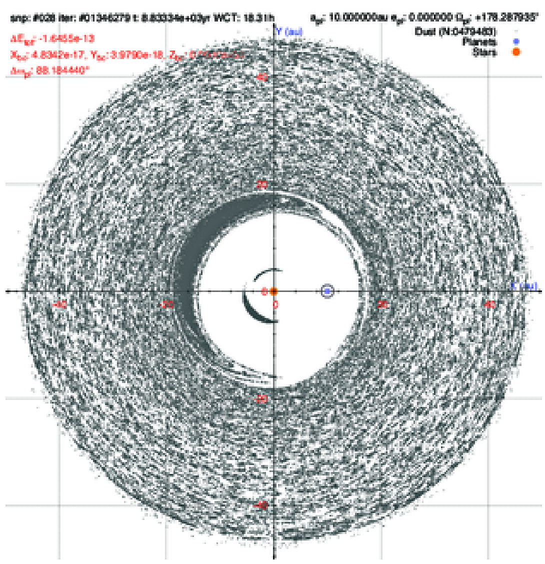


(4) The growing solid core is ejected from the trap in 0.5–1 Myr, depending on its mass (the larger the mass the sooner the ejection occurs). (5) Reaching a critical mass ($10-15\,M_\oplus$), the giant planet core starts to collect a massive envelope via the runaway gas accretion. (6) The giant planet opens a gap in the disc and undergo Type II migration, which is significantly slowed down due to the reduced viscosity in the dead zone *solving the fast Type II migration problem*. The large-scale vortices formed at the viscosity transition are naturally long-lived, thus they can act as *planetary factories* producing a system with multiple planets as the fast formation of a planetary embryo, its temporary trapping, and giant planet formation can happen continuously.

2.2 PLANNED THEORETICAL AND NUMERICAL INVESTIGATIONS

TO TEST THE VORTEX-AIDED PLANET FORMATION HYPOTHESIS, theoretical and numerical investigations will be performed by means of global hydrodynamical simulations modelling the gas flow in protoplanetary discs coupled to N-body integration modelling the dynamics of solid bodies. We will model the mass, momentum, and energy conservation equations of gas interacting with planets, as well as smaller solid bodies whose orbits will be calculated by direct N-body integrator. For the viscosity of the gas, we will apply the widely used α-prescription neglecting MHD effects, which will allow long-term (~ 1 Myrs) simulations. We will address steps (1) and (3)-(6) of vortex-aided planet formation scenario that can be modelled by the available numerical tools. To model step (2), we will apply a semianalytic presciprtion of dust grain growth described in Stepinski & Valageas (1997). We aim at investigating the following aspects: (i) the dust collecting efficiency of vortices to estimate the available solid material for the embryo growth phase; (ii) the formation of terrestrial planets and core of giant planets via mutual interactions of planetary embryos in the vicinity of vortices; (iii) the migration of growing terrestrial and giant planets in the vicinity of planet trap served by the vortex; (iv) the observable signatures of vortices and newly born planets embedded in young protoplanetary discs.

(i) DUST COLLECTION EFFICIENCY OF THE VORTICES is crucial in the vortex-aided planet formation scenario as they determine the amount of material available to build terrestrial planets or cores of giant planets. In this study, the dust accumulation inside the vortex will be self-consistently calculated by numerical simulations rather than approximated by a constant dust-to-gas mass ratio applied in the PI's former study (**Regály, Zs.** et al. 2012). We will also take into account the dust feedback effect on the gaseous vortex development. We will use a new dust module have already been added to our hydrodynamic solver (see a preliminary result on dust accumulation in a vortex on the right), which calculates the orbital evolution of dust particles by evaluating the drag force of gas. First, we investigate the dust feedback in 2D, then we extend our models to 3D. Significant amount of gaseous material can be collected by vortices, thus to include self-gravity in hydrodynamical simulations is of major importance. Therefore, we will use a Poisson solver in 2D cylindrical geometry based on fast Fourier algorithm (already has been developed by the PI), then apply it to 3D spherical geometry. The gas depletion due to photoevaporation or disc wind will be taken into account by approximating it with an exponential decay of gas density. With these improvements, we will be able to model the long-term evolution (~ 1 Myrs) of a vortex developed at viscosity transitions in a self-consistent manner, which is important for the next steps of our study of plant formation.



(ii) TERRESTRIAL AND GIANT PLANET CORES CAN FORM via the collision of planetary embryos and their interactions with the gas. We will investigate this formation scenario in the vicinity of a large-scale vortex. The mutual gravitational interaction of a large number of planetary embryos embedded in a gaseous disc can be modelled by the combination of a high-precision direct N-body integrator and a hydrodynamic solver in 2D or 3D geometries. In the N-body models, the treatment of embryo collisions will incorporate the mass and momentum conservation. To take into account the effect of the gaseous vortex on the mutual collisions and migration of planetary embryos, we will use well-tested hydrodynamic solvers with our high-precision N-body integrator. In this study, we will extend the model of Sándor et al. (2011), who found fast formation of a several Earth-mass planet in the vicinity of a planet trap in a 1D model. We aim at providing an approximation of the mass-growth function of planetary cores in the vicinity of a large-scale vortex to model the next step of multiple terrestrial and giant planet formation.

(iii) TERRESTRIAL AND GIANT PLANETS MIGRATE in Type I and Type II regimes, respectively, due to their interactions with the gaseous disc. Low-mass planets can be trapped temporarily in an overdense region near the vortex, thus their migration and trapping are likely affected by the enhanced mass growth occurring in these overdense regions. Extending the PI's earlier studies on vortex trapping in which the planet mass was fixed (**Regály, Zs.** et al. 2013), we will study Type I migration and temporary trapping of low-mass planets in the vicinity of a large-scale vortex assuming that the planet mass grows with time. First, the mass growth function will be approximated by an explicit function fitted to the simulations of Lissauer et al. (2009). To investigate the effect of the vortex on the Type I migration of a growing planet, we will run simulations assuming a mass-growth function given by our results obtained in step ii. After the solid core has reached a critical mass, the run-away gas accretion begins (Pollack et al. 1996). Since giant planets significantly distort the disc structure by opening a gap, they have strong effect on the vortex evolution, which in turn can affect the Type II migration of the giant planet. Therefore, we will investigate Type II migration of high-mass planets assuming that their mass grows due to the run-away envelope accretion. The run-away growth of high-mass planets will be approximated such that a certain amount of the gas (prescribed by the accretion efficiency) accumulated inside the planetary Roche-lobe will be added to the planet mass at each time-step (Kley 1999). We plan to carry out hydrodynamical simulations to study these effects first in 2D then we will extend our models to 3D.

(iv) OBSERVATIONAL PREDICTIONS WILL BE GIVEN to test the hypothesis of vortex-aided planet formation based on our simulations of dust collection and vortex evolution (ste i), planetary growth (step ii), and migration (step iii). In order to study the observability of dead zone vortices in sub-millimetre interferometric images, we will calculate synthetic ALMA images at 880 μm like our team did in **Regály, Zs.** et al. (2012). The dust temperature will be determined in thermal Monte-Carlo simulations based on the dust distribution derived from concurrent dust-hydro simulations; images in the dust continuum emission will be calculated using a ray-tracing method. For the temperature calculation and ray-tracing we will use the state-of-the-art 3D radiative transfer code RADMC-3D (Dullemond et al, in prep). Finally, the interferometric ALMA observations will be simulated using the CASA package. To model the molecular line emission of discs perturbed by a massive embedded planet, we will calculate synthetic observations in bright molecular lines (e.g, CO, OH). The line profiles will be calculated with radiative transfer tools using snapshots of the density, velocity, and temperature distributions of the emitting gas given by our hydrodynamic simulations. For preliminary investigations, the PI's fast semi-analytic line radiative transfer code (**Regály, Zs.** et al. 2010), while for detailed studies, the 3D radiative transfer code RADMC-3D or LIME (Brinch & Hogerheijde 2010) will be used. Based on the expertise of the project members (A. Juhász, Á. Kóspál, A. Móor) in observations with cutting edge instruments/telescopes such as ESO-VLT/CRIRES and ALMA, the team plans to submit observing proposals to ESO to detect vortex and planet signals in transition discs.

3 METHODOLOGY

TOOLS TO PERFORM THE PLANNED HYDRODYNAMICAL EXPERIMENTS have been successfully used in the PI's former research. Due to the large computational demands of globally solving hydrodynamic equations on Myr time-scale in 2D and especially in 3D discs, we will use codes specifically developed for Graphical Processor Unit (GPU) accelerated hardware. For the hydrodynamic simulations in 2D, the PI has already been extended the capabilities of the GFARGO code (the GPU-based FARGO), while for 3D simulations FARGO-3D (the GPU-based 3D progeny of FARGO and GFARGO codes) will be used. Since both codes utilise a very fast advection method developed for studying planet-disc interactions, they can also be used to model the migration of planets embedded in a gaseous disc (Masset 2000). The gravitational interactions of modest number of planets (1-10) have already been implemented in GFARGO and FARGO-3D utilising a 5th order Runge-Kutta integrator. The vortex development near the viscosity transition and a simple treatment of planetary mass growth have also been implemented in the GFARGO and FARGO-3D by the PI. To investigate the dust feedback on the formation of vortices, we will update our dust advection module first in 2D (GFARGO), then in 3D (FARGO-3D).

FULLY GPU-BASED N-BODY DIRECT INTEGRATORS recently developed by the PI, will be used for modelling the gravitational interaction of a large number of embryos and planets in 3D in the vicinity of the vortex (Regály et al. 2016 submitted to ApJ). The fully GPU-based code HIPERION utilises 4, 6, and 8th order Hermite (Nitadori & Makino 2008) and 5-6th order Runge-Kutta methods with adaptive time-step, designed for long-term (10 Myrs) direct N-body simulations. To model the interactions of dust particles or a large number of embryos embedded in a vortex bearing gaseous disc, the PI combined the HIPERION N-body code with the GFARGO. Based on a preliminary calculation (see on page 4), accumulation of mm-sized dust particles in a large-scale vortex can be modelled in a couple of days assuming half a million particles. In the framework of the current project we will also integrate HIPERION with the hydrodynamic solver FARGO-3D. The code merging is feasible as GFARGO has the same CUDA-based implementation as FARGO-3D.

4 EXPECTED RESULTS

THE ULTIMATE GOAL OF THE PROPOSED RESEARCH is to answer the question: *Can terrestrial and giant planet formation be aided effectively by large-scale vortices developed at the dead zone edges of protoplanetary discs?* By modelling the dust accumulation in vortices, we will provide initial conditions for the formation of planetary embryos in vortices. Having estimated the production rate of planetary embryos, we will describe the process of the formation, trapping, and Type I migration of terrestrial planets and cores of giant planets affected by vortices. We will also describe the effect of the vortices and the suppressed viscosity in the dead zone to the Type II migration of growing giant planets. We will give a qualitative picture of the expected architectures of planetary systems formed via the vortex-aided scenario. Finally, we will compare the orbital configurations given by our simulations to those of observed in exoplanetary systems.

OBSERVATIONAL EVIDENCES will be sought at the important phases of the formation process of exoplanetary systems. Models of planet formation were so far challenging to test with observations due to the spatial resolution and sensitivity limitations of even the most powerful telescopes. We are, however, in the very moment when a new generation of telescopes and instruments come online (ALMA, SPHERES, CRIRES+) capable of spatially resolving the birthplace of planets. This will allow us to directly test various aspects of *vortex-aided planet formation* scenario.

5 RESEARCH BACKGROUND

HIGH PERFORMANCE COMPUTING ARCHITECTURE (HPC) is necessary for the proposed research as the global disc simulations on Myrs time scale require computationally demanding hydrodynamic and N-body calculations. Our experiences show that a single GPU can reach the computing capability of 10-100 CPUs depending on the problem at hand: for example 2D hydrodynamic simulation on a Myr time-scales requires several months for a single CPU, while it can be done in couple of days with a single GPU. For code development purposes our team will use the GPU-based HPC at Konkoly Observatory providing 3.5 TFLOP capacity. Product simulations will be done on NIIF HPC infrastructure providing about a hundred TFLOP capacity (being equivalent of using 50-100 GPUs simultaneously) in the framework of the PI's granted research application "New Directions in Planet Formation". The Hungarian Academy of Science supported our initiation in early 2016 to establish a 3D Numerical Astrophysical Laboratory, which is aimed at virtual rendering of 3D simulations for scientific and public communities.

COLLABORATIVE WORK is planned as the proposed research demands a broad range of theoretical and observational research. The project members on the theoretical part are experts in the field of the physics of planet-disc interactions and N-body simulations. The research on the dust feedback and disc self-gravity effects has already been initiated in the framework of an international collaboration with E. Vorobyov (University of Vienna). On the observational side, we will collaborate with the MTA CSFK Lendület Disc Research Group at Konkoly Observatory to work on sub-millimeter ALMA proposals and data reduction. We will extend our on-going collaborations with internationally renowned groups and scientists such as Prof. C. P. Dullemond (ITA, University of Heidelberg) and Prof. W. Kley (University of Tübingen).

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