Numerical Simulations of Planet-Disc Interactions
Workshop held in Cuernavaca, Mexico
November 20-24, 2017

Programme

Foreword

The talks have been broadly classified into three categories, explicited in the next page. Many of the abstracts could have actually fit into two categories, or even all three. Despite our classification being rather crude and sometimes inaccurate, it allows to get a mix of different topics every day, with input from observations, considerations on numerical methods and theory.

Start Time	Time Blocks
9:00 AM	35m

NUMPDI 2017

Talk schedule (mornings)

TIME	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
9:00 AM	F. Masset	S. Casassus	P. Pinilla	E. Lega (remote)	E. Bopp
9:35 AM	R. Dong	C. Hall	S. Dodson-Robinson (remote)	P. Benítez-Llambay	D. Velasco
10:10 AM	D. Muñoz	P. Artymowicz	S.-J. Paardekooper	G. Rosotti	F. Horrobin
10:45 AM	M. de Val-Borro (remote)	M. Han Veiga	T. Hanawa	Z. Zhu	Zs. Regály
11:20 AM	*Coffee break*				
11:55 AM	J. Shi	M. Flock (remote)	T. Hands	Zs. Sándor	A. Crida
12:30 PM	P. Granados	J. Fung	C. McNally	W. Lyra	
1:05 PM		N. Cimerman	M. Fletcher	A. Riols	
1:40 PM	*Lunch*				
2:15 PM					
2:50 PM					

Orange	*Numerical methods, codes, hardware*
Green	*Observations, connection between observations and theory, synthetic observations, dust dynamics*
Light blue	*Theory (discs, planet formation, tidal effects, MHD, GI, etc.)*

Contents

Mixed-platform cluster for disk-planet interaction and the hydrocode development

Pawel Artymowicz
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I will describe a very cheap but powerful cluster that we have constructed combining the computational platform of CPU, MIC (Xeon Phi) and GPU. It has a combined double precision arithmetic performance (theoretical) of about 80 TFLOPs. I will present a few speed tests in massively parallel statistical study of stability of planetary systems and in 3-D hydrodynamics on a Cartesian grid. We have gathered substantial experience in optimization of particle and hydrocodes and conclude that the 3 computational platforms are all in the same ballpark of processing throughput. We do not see a domination by GPU or any other platform. Each platform can thus be used on a part of the problem where it shows particular advantages. We are developing a multilevel, variable grid, multiple-timestep PPM hydrocode for disk-planet interaction, based on superposed global polar and local spherical grid(s). Our cluster, designed for this application, will leverage a considerable power of fast CPUs on local grids surrounding planet(s), and MIC coprocessors on large grids, where hundreds of threads run by each device can efficiently be used on large portions of the upper-level grid. GPUs can be used for optional self-gravity calculation (in single precision) or to run separate GPU-only code. The goal is to study the migration of Earths and super-Earths embedded in a protoplanetary disk simulated by several billion cells, while resolving the flow down to the physical radius of the planet.

Planet-disk interactions with FARGO3D

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Planet-disk interactions and, particularly, the nonlinear dynamics close to a protoplanetary core embedded in the disk, are challenging problems far from being tractable by pure analytical calculations. Hence, sophisticated numerical simulations are mandatory in order to advance in this field. In this talk I'll present the code FARGO3D, a finite difference parallel magneto hydrodynamical code, and show its current capabilities. I'll focus on the most relevant details that make this code a suitable tool for planet-disk interaction studies.

Characterization of young accreting planets

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Since the early detections of planets around stars other than the sun, the astronomical community has gained a very good insight into the possible structure and dynamical behaviour of planetary systems. In parallel, our understanding of the disks around young stars, where these planets are formed has grown as well. Many processes of early stages of planet formation are now well understood through theoretical modelling and observations. There is a missing link between these early stages and the mature planetary systems we observe around so many stars. This least constrained part of our understanding is being investigated statistically by planetary population synthesis and observationally by searching for young planets embedded in planet-forming disks. With a new generation of instruments we expect to directly observe the accretion onto these young planets within disks. Such observations may allow us to put stronger constraints on the chemical and physical processes governing this phase of planet formation. The aim of this project is to study the feasibility to trace such planets in disks and to derive constraints on the conditions in their immediate vicinity during the late stages of their evolution. For this purpose, detailed dynamical models of a disk with an embedded planet will be created and continuously improved. The primary focus will be set on finding an appropriate treatment of the hydrodynamical and radiative processes within the disk. The resulting dynamical models are going to form the base for the creation of synthetic observations using more accurate radiative transfer models.

Warps in protoplanetary disks

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Inclination changes have often been invoked to explain protoplanetary disks observations, from azimuthal variations of scattered light, deviations from simple Keplerian rotation in the kinematics of molecular lines, or orientation changes with angular resolution. Well characterised examples can inform on the origin of central warps, on their role in disk evolution, and allow for new probes of physical conditions. In transition disks, the separation of the inner and outer disks by a radial gap allows firm constraints on the warp geometries. There is now a number of 4 examples of sharply warped transition disks, in which the outer disk is directly exposed to stellar light. In a couple of examples, the available data allow to estimate the temperature drop of the gas under the shadowed regions. Along with describing the existing warped systems, I will present a diagnostic of the outer disk mass based on the cooling timescale of the shadowed gas.

Small-scale aspects of the planet-disc interaction for low-mass planets

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The population of close-in super-Earths, with gas mass fractions of up to 10% represents a challenge for planet formation theory: how did they avoid runaway gas accretion and collapsing to hot Jupiters despite their core masses being in the critical range of $M_c \approx 10\ M_\oplus$? Previous three-dimensional (3D) hydrodynamical simulations indicate that atmospheres of low-mass planets cannot be considered isolated from the protoplanetary disc, contrary to what is assumed in 1D-evolutionary calculations. This finding is referred to as the recycling hypothesis. In this Paper we investigate the recycling hypothesis for super-Earth planets, accounting for realistic 3D radiation hydrodynamics. Also, we conduct a direct comparison in terms of the evolution of the entropy between 1D and 3D geometries. We clearly see that 3D atmospheres maintain higher entropy: although gas in the atmosphere loses entropy through radiative cooling, the advection of high entropy gas from the disc into th e Bondi/Hill sphere slows down Kelvin-Helmholtz contraction, potentially arresting envelope growth at a subcritical gas mass fraction. Recycling, therefore, operates vigorously, in line with results by previous studies. However, we also identify an "inner core" – in size ≈ 25 % of the Bondi radius – where streamlines are more circular and entropies are much lower than in the outer atmosphere. Future studies at higher resolutions are needed to assess whether this region can become hydrodynamically-isolated on long time-scales.

Migration of accreting planets

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When giant planets form in the protoplanetary disc, they accrete gas and migrate simultaneously. Here, I will present two aspects of the interplay between these phenomenons. (i) Before the planet can open a gap (above 200 Earth masses), it is subject to type I migration which, above 20 Earth masses is always inwards and fast (the corotation torque saturates). Therefore, there is a competition between accretion and migration, in order to reach a gap opening mass before falling into the central star. We find that the fast accretion of gas from the horseshoe region helps opening a gap before the semi-major axis to be reduced by more than a factor 2 (Crida & Bitsch 2017). (ii) Once a gap is open, the giant planet is in type II migration. In the classical picture, the planet follows the viscous spreading of the disc. This picture has been recently shown to be very approximate ; in fact, gas can cross the gap, which decouples the planet from the disc evolution. But when the planet accretes efficiently, it intercepts the flow and brings the migration rate back close to the classical one (Robert et al. 2017, EPSC). These results are based on FARGO simulations, with an accretion routine based on the standard Kley (1999) scheme with some modifications that will be presented.

A comparison of numerical simulations of a planet-disc system

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I will present the results of the EU-funded comparison of numerical simulations of a disc-planet system using grid-based and SPH codes. The main goal of the project was to investigate the reliability of 17 commonly-used codes and serve as a benchmark for future simulations. Several tests were run for simple 2-dimensional setups where a giant planet on a circular orbit around its host star opens a gap in a protoplanetary disc during hundred of orbits. Although the codes show good agreement on the general picture, there were some outstanding differences between the various algorithms. I will discuss the main results and the practical aspects of planning a code comparison that could be useful for future projects.

Connecting Observational and Theoretical Signposts of Planet Formation

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As sophisticated numerical models of planet-disk interactions combine with high-resolution ALMA (and soon JWST) observations of protostellar disks, we can hope to add more young, accreting planets to our exoplanet inventory. Yet disks' H2 gas reservoir, which provides the bulk of the mass for giant planet growth, is still hidden from observations, and CO emission lines give underestimates of both the disk mass and turbulent speed if the spatial distribution of CO is not known. I will discuss the ways ground-based and JWST observations can reveal the presence of hidden planets in disks and assess the limitations of current methods in characterizing both the solid and gas reservoirs available for planet formation. I conclude with a set of recommendations for how observers and theorists can work together to understand the planet-forming environment.

Connecting simulations of disk-planet interactions with observations of protoplanetary disks

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Because planets form in protoplanetary disks, the most direct and powerful way to learn how they form from observations is to directly watch them forming in disks. Thanks to a fleet of new instruments with unprecedented resolving power that have come online recently, we have just started to unveil structures in resolve images of protoplanetary disks, such as gaps, spiral arms, and azimuthal asymmetries, that are most likely associated with planets forming in disks. By comparing observations with theoretical models of planet-disk interactions, the masses and orbits of (unseen) planets may be constrained. Such planets help us directly test various planet formation models. I will review three topics in the field: (1) what are the state of the art disk observations that are providing the clearest signposts of planet formation in disks, (2) what kind of comparisons between observations and theoretical models are being done today, and (3) what have we learned so far about planet formation from these observations.

Code comparison project for migration of massive planets embedded in massive protoplanetary discs

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Code comparison project for migration of massive planets embedded in massive protoplanetary discs M. Fletcher, S. Nayakshin, D. Stamatellos, W. Dehnen, F. Meru, L. Mayer, H. Deng, K. Rice Most of type I planet migration studies so far were devoted to rocky planets migrating in a protoplanetary disc at separations of a few AU. Recently, over a dozen independent numerical investigations found that the type I migration regime is also relevant for a gas giant planet embedded in a large scale (100 AU), young and massive protoplanetary disc. The migration time in this regime is found to be as short as a few thousand years, suggesting that the vast majority of planets born by gravitational instability could migrate into the inner few AU disc and be tidally destroyed or swallowed by the host star (Boley et al 2010). On the other hand, other authors find that these planets should migrate in the type II regime, open deep gaps and stall at wide separations (e.g., Forgan and Rice 2013). Resolving the disagreement is absolutely crucial if we want to constrain the frequency of planet and brown dwarf formation by gravitational instability in young massive discs (cf. the contrasting conclusions of Vigan et al 2017 and Nayakshin 2017). We report a community driven effort to investigate the robustness of numerical modelling of the migration process in different simulation codes. The test problem comprises a giant planet, with an initial mass of either 2 MJ or 12 MJ, embedded in a massive (0.2 Solar Mass) protoplanetary disc at separation of 120 AU. We also test accreting (via the sink particle formalism) and non-accreting planet settings, comprising in total 4 different regimes. Currently, the comparison is performed between 6 SPH (PHANTOM, GADGET, SPHINX, SEREN, SPHNG, GIZMO) and 2 grid based codes (FARGO, mfm GIZMO). Our preliminary results show a qualitative agreement between the codes. Low initial mass planets migrate in rapidly in the type I regime, whereas the more massive planets open deep gaps and stalls at around 80 AU. However, quantitatively there is less agreement than expected, with the migration rate varying by up to a factor of 3 between the codes. We explore how different artificial viscosity implementations affect the results. Gas accretion onto the planet also adds to the complexity of the problem; with accretion turned off the tested codes are generally more consistent with each other.

The Close-In Planet Forming Environment of Protoplanetary Disks

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Many planets orbit within an AU of their stars, raising questions about their origins.Particularly puzzling are the planets found near the silicate sublimation front. We investigate conditions near the front in the protostellar disk around a young intermediate-mass star, using the first global 3-D radiation non-ideal MHD simulations in this context. The results show magnetorotational turbulence around the sublimation front at 0.5 AU. Beyond 0.8 AU is the dead zone,cooler than 1000 K and with turbulence orders of magnitude weaker. A local pressure maximum just inside the dead zone concentrates solid particles, allowing for efficient growth. Over many orbits, a vortex develops at the dead zone's inner edge, increasing the disk's thickness locally by around 10

Why are Warm Jupiters Rare?

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The majority of gas giants (planets of masses around 10^2 Earth masses) are found to reside at distances beyond 1 au from their host stars. Within 1 au, the planetary population is instead dominated by super-Earths of 2-20 Earth masses. We explain this particular feature of planetary system architecture using a combination of planet migration, pebble accretion and gas accretion. Using long-term (up to 10^5 years) 2D hydrodynamical simulations of disk-planet interaction, we track planet migration and pebble accretion until both come to an end: planet migration is stopped by disk feedback, and pebble accretion by the planet generating an outer pressure maximum that stops the inflow of pebbles. We then follow the planet's evolution using 1D gas accretion models to determine whether the planet will accrete enough gas to undergo runaway gas accretion and become a gas giant. Our results show that more massive planetary cores are formed at larger radii, and so only the outer cores will undergo runaway accretion. In an inviscid minimum mass solar nebula, the dividing radius between cores that do and do not become gas giants is between 0.3 to 0.7 au, depending on the assumptions made in the opacity of their atmospheres. If the disk gas mass is lower, this dividing radius increases. This result provides an explanation for the suppression of gas giant formation within 1 au, and has implications on disk and planet properties.

Consequences of eccentricity and inclination damping for the in-situ formation of STIPs

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In Boley, Granados, and Gladman (2016), we proposed that hot and warm Jupiters could form in-situ from the consolidation of planets in meta-stable, high-multiplicity System with Tightly-packed Inner Planets (STIPs) in the presence of gas. Under this hypothesis, the timing of instability within the STIP relative to the gas depletion timescale can lead to a wide range of planetary diversity, from short-orbital period gas giants to high-density, massive planets. The simulations used Kepler-11 as a base and assumed that a gas giant could form instability in the gaseous disc led to the consolidation of a 10 Mearth core. The results showed that such consolidation could work, in principle. However, in the simulations we excluded the effects of eccentricity and inclination damping. For the new simulations, we implemented a prescription of gaseous tidal damping in our version of the Integrator with Adaptive Time-Stepping of 15th-order (IAS15). We explore this effect in the consolidation paradigm. For the parameters so far explored, gas damping significantly increases the stability of the system, although consolidation does occur in some cases. Our version of IAS15 can be modified to include prescriptions for planet-disk interactions and that would be least computational expensive than hydrodynamic simulations.

From simulations to observations: synthetic imaging in the ALMA era

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We live an unprecedented era of observational astronomy, with a panoply of morphological features being revealed by instruments such as ALMA and SPHERE. I discuss some recent work simulating ALMA observations of the Elias 2-27 system, and emphasise the value of generating synthetic observations from disc-planet simulations for use by the broader community.

Numerical Evaluation of the Coriolis Force on the Cartesian Grid

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We are studying an accreting young binary based on numerical simulations. The simulations are performed on the Cartesian grid fixed on the frame co-rotating with the binary. Then the Coriolis force appears as a source term in the hydrodynamical equations to be solved. We show that the specific angular momentum of a gas element is well conserved if a half of the Coriolis force is evaluated from the mass flux. The other half is evaluated from the cell average momentum density. It is also demonstrated that the Coriolis force produces spurious change in the specific angular momentum and rest frame velocity, if it is evaluated either solely from the cell average momentum or from the mass flux. We discuss the validity of our method of evaluating the Coriolis force. It is shown that our solutions satisfy the equation of momentum conservation in the rest frame without truncation error in space. The numerical error is serious around shock waves since the numerical mass flux is largely different from the momentum thereof. The shock waves drive gas accretion through angular momentum transfer and should be simulated accurately.

Breaking mean-motion resonances during Type I planet migration

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We present two-dimensional hydrodynamical simulations of pairs of planets migrating simultaneously in the Type I regime in a protoplanetary disc. Convergent migration naturally leads to the trapping of these planets in mean-motion resonances. Once in resonance the planets' eccentricity grows rapidly, and disc-planet torques cause the planets to escape resonance on a time-scale of a few hundred orbits. The effect is more pronounced in highly viscous discs, but operates efficiently even in inviscid discs. We attribute this resonance-breaking to overstable librations driven by moderate eccentricity damping, but find that this mechanism operates differently in hydrodynamic simulations than in previous analytic calculations. Planets escaping resonance in this manner can potentially explain the observed paucity of resonances in Kepler multi-transiting systems, and we suggest that simultaneous disc-driven migration remains the most plausible means of assembling tightly-packed planetary systems.

Structure preserving schemes for protoplanetary disk simulations

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The early stages of planet formation are generally hard to model numerically. We study different high order numerical schemes, namely, Discontinuous Galerkin (DG) methods and Residual Distribution (RD) methods and their structure preserving properties (in particular, preservation of steady states (well balanced property) and conservation of angular momentum, both in Cartesian and unstructured triangular meshes). In particular, I would like to present a novel high order well balanced DG scheme that captures steady states beyond hydrostatic equilibrium, and a RD method which preserves angular momentum, both for multi-dimensional Euler system.

Integration of Particle Protoplanetary Disks Using CPUs and Coprocessors

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We compare the capabilities of modern CPUs and coprocessors (Intel Xeon Phi) for massively parallel simulations of protoplanetary disks. We look at a particle model of a protoplanetary disk, containing up to several billion particles. This can be integrated in several days of computation for astrophysically interesting timescales (1e3-1e5) orbits on a small hybrid cluster, such as the one we have built at UTSC. We discuss a particular application of a Nx3B simulation of a particle disk interacting with a binary system, implemented in Fortran90 and optimized for the Intel Xeon Phi platform. This project is part of our investigation of planet migration in disks. With a large number of particles and varying timesteps within the Roche lobe, we achieve high resolution around the planet. This allows us to describe the flows leading to type III planetary migration as well as to study the evolution of the spin of a planet. We simulate planets with masses ranging from Earth to Jupiter mass in varying disk masses and profiles to describe the observed differences in disk perturbation and migration rates.

The FARGOCA code: results and perspective

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The code FARGOCA (FARGO with Colatitude Added at OCA,) is based on the FARGO code extended to 3 dimensions with the additional introduction of an energy equation to provide a realistic modeling of radiative effects. The fluid equations are solved using finite-differences with a time-explicit-implicit multistep procedure. The code is parallelized using a hybrid combination of MPI between the nodes and of OpenMP on shared memory multi-core processors. The code, operational since 2013, has been used for several studies of planetary migration in fully radiative discs. The recent implementation of a nonuniform grid geometry (like for the PEnGUIn code) gave us the possibility to achieve high enough resolution for the study of 3D flow in the vicinity of low massive planets and to address questions like the formation of super-Earths and giant planets. I will review some of the results obtained and discuss the possible code-upgrade that we would like to have in order to follow the problematics of gas-disc interactions in the era of discs observations.

Low mass planet migration in magnetically torqued dead zones

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Motivated by models suggesting that the inner planet forming regions of protoplanetary discs are predominantly lacking in viscosity-inducing turbulence, and are possibly threaded by Hall-effect generated large-scale horizontal magnetic fields, we examine the dynamics of the corotation region of a low-mass planet in such an environment. The corotation torque in an inviscid, isothermal, dead zone ought to saturate, with the libration region becoming both symmetrical and of a uniform vortensity, leading to fast inward migration driven by the Lindblad torques alone. However, in such a low viscosity situation, the material on librating streamlines essentially preserves its vortensity. If there is relative radial motion between the disc gas and the planet, the librating streamlines will no longer be symmetrical. Hence, if the gas is torqued by a large scale magnetic field so that it undergoes a net inflow or outflow past the planet, driving evolution of the vortensity and inducing asymmetry of the corotation region, the corotation torque can grow, leading to a positive torque. In this paper we treat this effect by applying a symmetry argument to the previously studied case of a migrating planet in an inviscid disc. Our results show that the corotation torque due to a laminar Hall-induced magnetic field in a dead zone behaves quite differently from that studied previously for a viscous disc. Furthermore, the magnetic field induced corotation torque and the dynamical corotation torque in a low viscosity disc can be regarded as one unified effect. This leads to the prediction of four distinct new regimes of low mass planet migration behaviour.

Orbital Migration with Steady Accretion: Binaries and Massive Planets

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I present new moving-mesh simulation results of binary/planet-disk interaction under the assumption that the primary and secondary masses are actively accreting from the surrounding gas. I focus on the detailed torque balance and its effect on the orbital elements of the binary resolving the accretion flows inside the two Roche lobes, which can contribute to the net torque, thus influencing the evolution of semi-major axis and eccentricity. I also discuss how moving-mesh simulations can probe difficult-to-simulate configurations, such as highly-eccentric binaries. I further describe numerical techniques and limitations. Finally, I briefly elaborate on the physical implications of these results. In binaries of mass ratios close to 1, the net torque is positive and the semi-major axis tends to expand. This unexpected outward binary migration has important implications for the formation of close binaries (a¡0.4 AU). It also challenges the common assumption that circumbinary disks can aid the orbital decay and subsequent merger of super-massive binary black holes, a challenge known as the "last parsec problem".

Multidimensional Upwind Methods on Unstructured Grids

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I will introduce a multidimensional generalization of the Roe solver, acting on an unstructured grid. The main advantages over traditional Riemann solvers are that dimensional splitting is avoided and that source terms are easily incorporated in the framework. An unstructured grid provides unprecedented opportunities to obtain very high resolution locally. I will discuss the prospects for simulating disc-planet interactions.

Rings, gaps, and cavities: origins and observational perspectives to distinguish them

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Recent multi-wavelength observations of protoplanetary disks have revealed fascinating structures, such as: multiple rings/gaps, asymmetries, and spiral arms. The most common explanation to understand the origin of these structures is embedded planets. However, alternative models can create similar structures in the gas and dust density distribution of protoplanetary disks. In this talk I will present recent theoretical predictions of models that include a dead zone and/or MHD winds in the context of transition disks. In addition, I will present the effect that several snow lines can have on the dust evolution, following the growth, fragmentation and dynamics of multiple dust size particles. Finally, I'll introduce some observational perspectives to distinguish between different possibilities for the origin of rings, gaps, and cavities in protoplanetary disks.

Vortex-aided planet formation

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"New directions in understanding planet formation: vortex-aided planet formation" is a four-year research project at Konkoly Observatory. The research addresses several unsolved problems of current theory of planet formation by a novel concept: the planet formation in anticyclonic vortex developed at the outer edge of discs's accretionally inactive zone. The new scenario may solve the problems related to the formation of planetesimals, too fast planetary migration, and slow formation of giant planets. We address several aspects of this concept by means of coupled hydrodynamical and N-body simulations. In my presentation i show our preliminary results regarding the vortex formation and dust dynamics modelled by the GPU-based hydrodynamical code GFARGO coupled to our own developed GPU-based N-body code HIPERION.

Gravitational instability and its interaction with the MRI in astrophysical discs

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Though usually treated separately, the magnetorotational and gravitational instabilities (MRI and GI) may coincide at certain radii and evolutionary stages of protoplanetary discs. Their mutual interactions could profoundly influence several important processes, such as accretion variability and outbursts, fragmentation and disc truncation, or large-scale magnetic field production. Direct numerical simulations of both instabilities are computationally challenging and remain relatively unexplored. In this talk, I will present a set of 3D vertically stratified shearing-box simulations, combining self-gravity and magnetic fields. I will show that gravito-turbulence greatly weakens the zero-net-flux MRI and that in the limit of efficient cooling (and thus enhanced GI), the MRI is completely suppressed, and yet strong magnetic fields are sustained by the gravito-turbulence. However the criterion for disc fragmentation and clumps formation do not seem to be changed in presence of a zero net flux magnetic field. I will finally discuss the preliminary results in case of a net vertical flux and the implications for astrophysical discs.

Observing planet-disc interaction in the ALMA era

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In the era of ALMA, we finally have a chance of observing disc-planet interaction. I will first discuss the prospects for observing gaps opened by planets using optically thin CO transitions. In the rest of the talk I will mostly focus on the interaction with the dust which is more easily observed. I will present a semi-implicit dust implementation for the grid-based code FARGO that does not need short timesteps even in the case of tightly coupled particles. I will then discuss how the planet mass opening gaps in the dust depends on the disc temperature and viscosity. I will highlight in particular how opening a gap in the dust does not require a pressure maximum in the gas, as often assumed, but can be due only to a "traffic jam" effect. If a pressure maximum does form, I will show that its distance from the planet depends on the mass of the planet and only mildly on the magnitude of viscosity. This provides a method for estimating the planet mass from observations of dust gaps now becoming common. Lastly, I will discuss how this picture changes if the planet is migrating, showing how in general migration hinders the opening of gaps. Since observations of gaps, and consequently simulations of dust, are now becoming common, I will advocate that it is important to perform a code-comparison project among the different dust algorithms. If time allows it, I will finish with other recent results where I will highlight the importance of running the simulations for very long timescales ($> 10^5$ orbits), now becoming possible using GPUs, to predict the planet eccentricity growth, showing that the long-term behaviour is the opposite of the short-term one.

Planet formation in pressure maxima of protoplanetary disks

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In the classical core-accretion scenario rapid inward migration of protoplanets and long accretion timescales of large (100 km) planetesimals may not favor the formation of giant planets within the limited lifetime of protoplanetary disks. A possible solution to the above problem could be the existence of planet traps, where the torques responsible for migration vanish. Planet traps can appear at special locations of disks such as density inversions, or sudden changes in dust opacity. Moreover, rapid inward migration of protoplanets might also be slowed down, halted or even reversed by the heating torque, which is due to the planetesimal accretion onto the surface of the growing embryo. The case of a planet trap effected by a density maximum is particularly interesting, since a pressure maximum may also develop in connection. Pressure maxima act as dust traps, collecting grains, and helping their further growth via either coagulation or drag-induced instabilities. In a recent work we numerically investigate the radial drift of pebbles and planetesimals, and planet migration to pressure maxima in a time evolving 1D disk model, and their effect on the formation of massive cores as triggering the gaseous runaway accretion phase. The equations governing the growth of the solid core by planetesimal and gas accretion are also solved simultaneously. Our simulations show that the pressure maxima generated at the edges of the low-viscosity region of the disk act as planet migration traps, and that the pebble and planetesimal surface densities are substantially increased due to the radial drift towards pressure maxima locations implying a significant shortening of the giant planet formation timescales. Pressure maxima generated at the edges of a low-viscosity region of a protoplanetary disk seem to be preferential locations for the formation and trap of massive cores.

numerical simulations of circumbinary disks

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Circumbinary disks (disk around a pair of gravitating objects) can be found around many astronomical objects. They are natural outcome of hierarchical galaxy formation and are often observed around protobinary stars. In this talk, I will discuss how the gravitational torque of the binary reshapes the circumbinary disk while still maintains its accretion based on MHD/hydro simulations. The changes of disk morphology found in simulations consist of a zoo of interesting dynamical features such as a low-density gap, narrow and high-velocity spiral gas streams, and a high-density lump adjacent to the disk edge, which could be used observationally to either identify the binary or measure its properties. At last, if time permits, I will talk about some progress regarding simulate the circumbinary disk with 3d hydrodynamic simulations.

A 2-D Cartesian implementation of High Order Discontinuous Galerkin methods over GPU and application to embedded planets

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The availability of computational resources such as graphics processing units (GPUs) has brought interest in compute intensive methods, whose performance is compute bound rather than memory bound. The Discontinuous Galerkin method having a small stencil and being compute intensive fits these requirements. Here we present a high-order Discontinuous Galerkin code, a 2-dimensional Cartesian code implemented to run in parallel over several GPUs. A simple disc-planet setup is used to compare the behavior of this code against the one exhibited by FARGO3D. We make use of the corotation torque as a mean to quantify the numerical viscosity of the code.

Applications of Spiral Density Waves: from Circumstellar disks to Circumplanetary Disks

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Recently commissioned telescopes and instruments (e.g., Subaru, GPI, VLA, ALMA, EVLA) are now finally able to resolve the protoplanetary disk down to the scale of a planet's immediate assembly zone, and a rich variety of disk features have been revealed: gaps, large scale disk asymmetry, and spiral arms. Spiral arms are particularly interesting since they are common features from the planet-disk interaction. If the observed spiral arms are due to embedded planets, the spirals provide strong constraints on the disk structure and the embedded planet properties. In this talk, I will discuss some recent progress on spiral arm theory, especially multiple gaps induced by a single planet, and how we can apply them to gaps in circumstellar disks (e.g. HL Tau). Then I will apply these theories to the tiny disks around the young planet: circumplanetary disks. I will suggest that spiral shocks can lead to efficient accretion in circumplanetary disks. Such accretion process can release a lot of energy and these circumplanetary disks can be lampposts for young planets in disks.

Start Time	Time Blocks
9:00 AM	35m

NUMPDI 2017

Talk schedule (mornings)

TIME	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
9:00 AM	F. Masset	S. Casassus	P. Pinilla	E. Lega (remote)	E. Bopp
9:35 AM	R. Dong	C. Hall	S. Dodson-Robinson (remote)	P. Benítez-Llambay	D. Velasco
10:10 AM	D. Muñoz	P. Artymowicz	S.-J. Paardekooper	G. Rosotti	F. Horrobin
10:45 AM	M. de Val-Borro (remote)	M. Han Veiga	T. Hanawa	Z. Zhu	Zs. Regály
11:20 AM	*Coffee break*				
11:55 AM	J. Shi	M. Flock (remote)	T. Hands	Zs. Sándor	A. Crida
12:30 PM	P. Granados	J. Fung	C. McNally	W. Lyra	
1:05 PM		N. Cimerman	M. Fletcher	A. Riols	
1:40 PM	***Lunch***				
2:15 PM					
2:50 PM					

Numerical methods, codes, hardware (orange)

Observations, connection between observations and theory, synthetic observations, dust dynamics (green)

Theory (discs, planet formation, tidal effects, MHD, GI, etc.) (light blue)