Asteroids: New Observations, New Models
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Linking the Origin of Asteroids to Planetesimal Formation in the Solar Nebula

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Abstract. The asteroids (more precisely: objects of the main asteroid belt) and Kuiper Belt objects (more precisely: objects of the cold classical Kuiper Belt) are leftovers of the building material for our earth and all other planets in our solar system from more than 4.5 billion years ago. At the time of their formation those were typically 100 km large objects. They were called planetesimals, built up from icy and dusty grains. In our current paradigm of planet formation it was turbulent flows and metastable flow patterns, like zonal flows and vortices, that concentrated mm to cm sized icy dust grains in sufficient numbers that a streaming instability followed by a gravitational collapse of these particle clump was triggered. The entire picture is sometimes referred to as *gravoturbulent formation of planetesimals*. What was missing until recently, was a physically motivated prediction on the typical sizes at which planetesimals should form via this process. Our numerical simulations in the past had only shown a correlation between numerical resolution and planetesimal size and thus no answer was possible (Johansen *et al.* 2011). But with the lastest series of simulations on JUQUEEN (Stephan & Doctor 2015), covering all the length scales down to the physical size of actual planetesimals, we were able to obtain values for the turbulent particle diffusion as a function of the particle load in the gas. Thus, we have all necessary data at hand to feed a 'back of the envelope' calculation that predicts the size of planetesimals as result of a competition between gravitational concentration and turbulent diffusion. Using the diffusion values obtained in the numerical simulations it predicts planetesimal sizes on the order of 100 km, which suprisingly coincides with the measured data from both asteroids (Bottke *et al.* 2005) as well from Kuiper Belt objects (Nesvorny *et al.* 2011).

Keywords. hydrodynamics, instabilities, turbulence, Kuiper Belt, asteroids, solar system: formation

1. Introduction

Planet formation is a beneficial side effect of star formation. It is the gas and dust around young stars that does not get accreted directly during the collapse of a cloud core due to angular momentum conservation that will form a planetary system. The goal of our current research activities is to better understand the properties and diversity of planets around distant stars as well as in our own solar system. Starting with numerical simulations of the star formation process we aim to understand the stages of disk formation and thus via a calibration on actual disk observations the initial mass and angular momentum distribution of disks as initial conditions for planet formation. In these disks we study all possible sources of turbulent disk evolution from self-gravity, via magnetic fields to classical hydro dynamical instabilities. Latest developments in the field include deriving various observables for different sources of turbulence, which in conjunction with simulations of planet disk interaction are used to interpret the wealth of observations coming online from interferometers working with many kilometre sized base-length in the submillimeter band, e.g. the Atacama Large Millimeter Array (ALMA

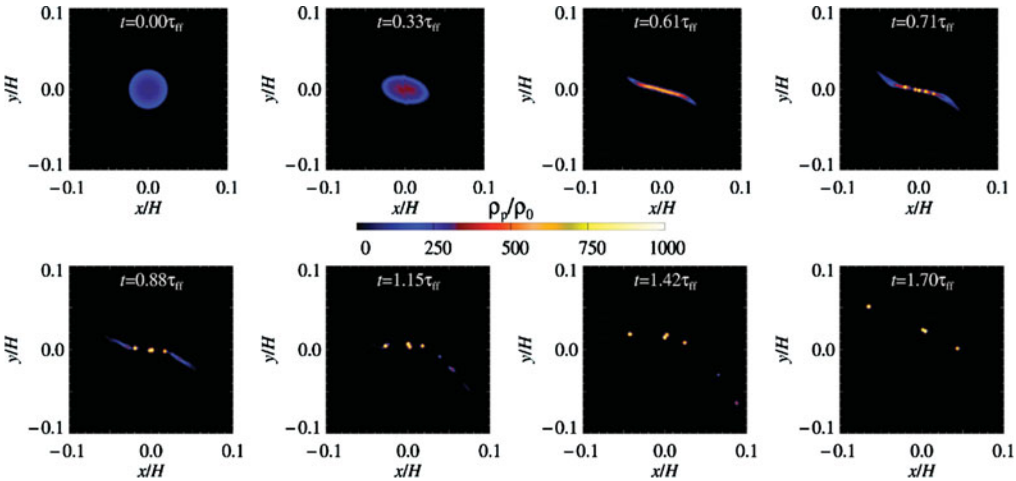

Figure 1. A series of snapshots following the collapse of a particle heap at 10 % of the local Roche density (see text) under its own gravity embedded in an accretion disk around a young star. Colours indicate the particle density. The initial spherical cloud gets sheared apart by Keplerian shear, or in other words by the tidal forces exerted from the star, because its internal density is lower than the local Roche density. Then, its local subregions that exceed the Roche density, collapse into a group of many planetesimals around 100 km in size. This 3D Hydro Dynamical Simulation was performed with the Pencil Code on the JUQUEEN cluster (see PhD thesis by Karsten Dittrich (2013)).

Partnership *et al.* 2015), to modern high resolution and high contrast cameras on the larges optical telescopes, e.g. SPHERE (Benisty *et al.* 2015). Lastly, we and our collaborators want to follow all evolutionary steps of planets from small dust grains and snow flakes via planetesimals to rocky and gaseous planets, part in order to feed population synthesis with better data, part to better interpret disk observations, and part to study the chemical composition of planets - a question of special relevance to understand the formation of life on earth and elsewhere.

The fundamental motivation for this letter is that by assuming the paradigm of planetesimal formation via gravitational fragmentation of locally concentrated dust, in either zonal flows or vortices - for which we now have a parameterised model - we seek answers to the following questions:

• Can we trace back the origin of Asteroid material, i.e., the place in the disk it has formed, before drifting in and getting transformed to planetesimals? Can we relate this to its composition (ice, water, volatiles, refractory, etc.)?

• What is the planetesimal to pebble ratio in the young asteroid belt? I.e., how much of the local dust population is not yet in planetesimals?

• Can we determine the parameter range for a semi-analytic planetesimal formation model, based on the asteroid belt? I.e., can we exclude certain parameters for disk and dust evolution in the solar nebula?

In this letter we present our latest understanding of the initial mass function in terms of a characteristic minimum size of planetesimals based on numerical experiments as well as analytic derivations.

2. Gravoturbulent Formation of Planetesimals

In a series of papers (Johansen *et al.* 2006, Johansen *et al.* 2007 and Johansen *et al.* 2011) we explained the formation of planetesimals via the process of gravoturbulence.

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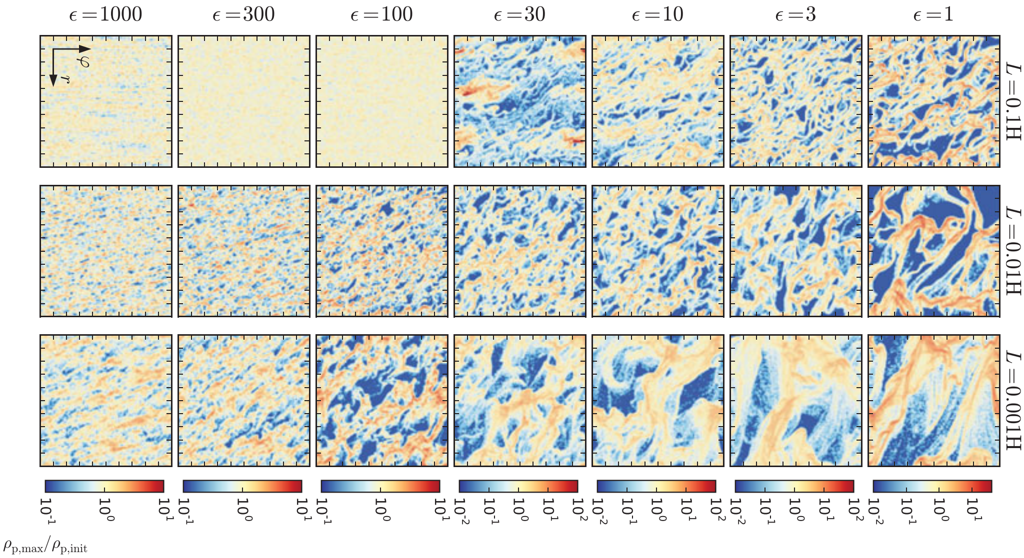

Figure 2. Overview of our parameter study to estimate diffusivities for the streaming instability on small physical length scales $L = 0.1\,H$ to $L = 0.001\,H$. We thereby investigate high dust–to-gas density ratios ϵ from 1 up to 1000, to mimic a wide range of phases within a collapsing particle clump. Color represents the local dust-to-gas ratio with red high and blue low values (please note the difference in scaling for the different ϵ simulations). One can notice here that even for very high ϵ values, where particles seem to dominate (left three rows), the SI can still be active on small scales (lowest row). For a detailed discussion of the results we refer to an upcoming paper by Schreiber *et al.* (in prep).

Here, it is magnetic fields that trigger the formation of zonal flows, which in turn concentrate particles up to dust-to-gas ratios $\epsilon = \rho_{\rm p}/\rho_{\rm g}$ of order unity. Then, a second instability kicks in, based on the feedback of the dust onto the gas - the streaming instability. The action of this instability is two fold: A: It concentrates the dust even further up to values that locally exceed the critical Roche density. Roche density is the density that a gravity bound body needs to withstand the tidal forces of a second more massive body, for instance a close by planet or here: the sun. And B: Destroying local particle concentration via turbulent diffusion on small scales. Exceeding the Roche density is the condition that self gravity is locally stronger than the tidal forces from the star, i.e. objects respectively particle clumps of lower density than the Roche density will not collapse but get tidally sheared apart (see Fig. 1 from the PhD thesis of Karsten Dittrich 2013). Also, comets are known to break apart once they pass the gravity field of a planet in a way that their internal density is lower than the local Roche density set by the planets mass and the distance from its center (see the break up of comet Shoemaker-Levy 9 (Asphaug & Benz 1996) and its following impact on Jupiter). In the case that gravity wins, e.g., that the local density exceeds the Roche density, a planetesimal can form. In Fig. 1 one finds that even if the initial cloud is sheared apart, it forms fragments, which individually can exceed the Roche density and then collapse to planetesimals. Unfortunately, the regions that exceed the Roche density are at the resolution limit of our numerical grid. Therefore, we started looking for a physical criterion on the smallest possible fragments that would withstand the tidal forces, while still resolving the turbulence of the gas. A particle clump at Roche density without any internal pressure will collapse on the free fall time $t_{\rm ff} \approx \Omega^{-1}$ with Ω being the local Keplerian frequency around the central star. As particles feel friction with the gas during their gravitational contraction, this time

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gets longer proportional to the friction time τ_f defined via $\dot{v} = -\frac{\delta v}{\tau_\mathrm{f}}$. The friction time describes the friction between a particle of given mass and size with its surrounding gas. If particles are smaller than the mean free path of the gas, the drag formulae for the Epstein regime have to applied, otherwise the aerodynamic via Stokes drag is valid. For typical particle sizes in protoplanetary disks the dimensionless friction time is given as the Stokes number $St = \tau_\mathrm{f}\Omega$. In the astrophysical context the Stokes Number is defined on the global dynamical time scale of the system, i.e., the orbital frequency of the accretion disk, rather than via the unknown timescale relevant for the dissipation scale. Particles of $St = 1$ are the fastest radially sedimenting objects in a radially pressure supported accretion disk. Our numerical simulations (Birnstiel *et al.* 2012) on particle growth and disk evolution have shown that typical values for particles dominating the radial inward drift of particles is around $St = 0.1$. Larger Stokes numbers, i.e., larger sizes, will rarely be available because they either rain out towards the star or destroy each other by collisional fragmentation. Nevertheless, the radial inward mass-flux of solids drifting inward is on the order of $10^{-6} M_\mathrm{Earth}/yr$ (Birnstiel *et al.* 2012), providing the necessary building material for planetesimals in particle traps.

In the case of Stokes numbers smaller than unity the particle clump contraction time (or sedimentation time for the case of self gravity) is on the order of $t_\mathrm{s} \approx \frac{t_\mathrm{ff}}{St}$ (Shariff & Cuzzi 2015). Yet, if the local dust concentration is diffused via the turbulent dust and gas motion with diffusivity D, a clump of size l gets diffused on the typical time scale of

$$t_\mathrm{d} = l^2/D. \tag{2.1}$$

If one compares now the time scale of diffusion versus sedimentation $t_\mathrm{d} = t_\mathrm{s}$ one can derive a size prediction of clumps to withstand internal diffusion at

$$l \approx \sqrt{\frac{D}{St\Omega}}. \tag{2.2}$$

In combination with the knowledge that the clump had already Roche density one can determine the mass of the resulting planetesimal as $m_\mathrm{p} = \frac{4}{3}\pi l^3 \rho_\mathrm{p}$. What remains to be determined is the diffusivity D for typical dust-to-gas ratios and length-scales at which planetesimal formation is thought to occur.

3. High resolution studies of the streaming instability

Hydro- and magneto-hydro-dynamical instabilities lead to non-laminar flows within proto-planetary disks (Klahr *et al.* 2003, Dittrich *et al.* 2013). Many of those non-laminar features are known to produce dust over-densities via the local trapping of radially sedimenting particles (sedimentation towards the central star), such as zonal flows, and vortices, resulting in axisymmetric and non-axisymmetric structures (Flock *et al.* 2015). Though, they are short-lived in terms of viscous disk evolution they are long-lived in terms of the disk dynamics. In particular, the concentration of dust as well as the collapse of a particle clump to a planetesimal is supposed to occur within a few local orbits. As shown in several papers in the last years particle over densities are self amplifying over a certain threshold due to the streaming instability (SI) (Youdin & Johansen 2007), which was numerical investigated on large scales ($\geqslant 0.1H$) (Johansen & Youdin 2007).

Following this idea, planetesimal collapse must happen in areas where the SI is already active and will maintain to be active during the entire collapse phase. Here, one can expect that for large dust-to-gas ratios the SI should become weaker, because in the extreme case of having only dust there are no more hydro-instabilities, and this is indeed what we see for numerical simulation at high ϵ-values.

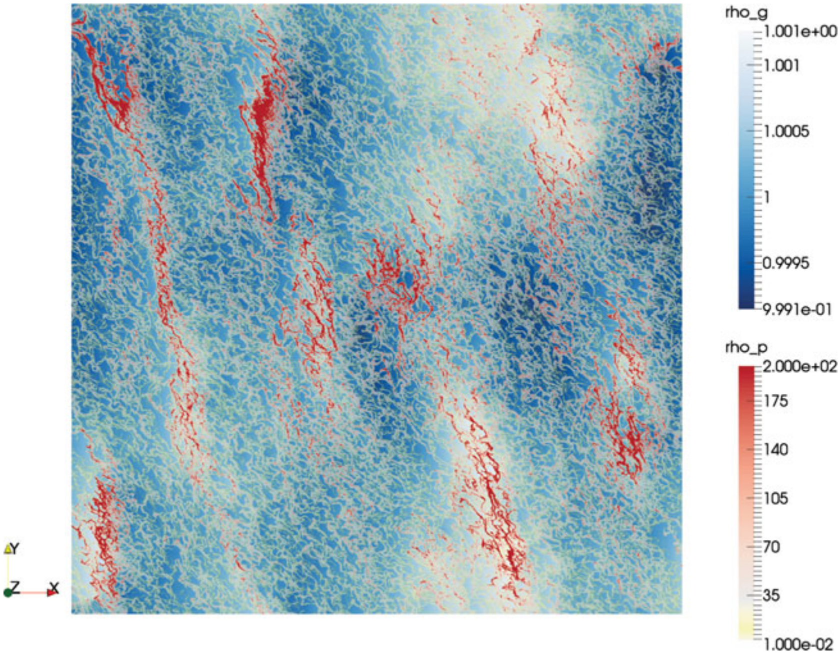

Figure 3. This snapshot shows our largest streaming instability investigation so far, with a resolution of 1250^2 and $1.6e7$ swarm particles. This snapshot shows in blue the underlying gas density field. On top of it in red to white is plotted the particle density. The particles show a typical streaming instability pattern over the whole domain (white) and additionally (red) particle dominated regions which are long lived and highly particle concentrated.

Thus, in a forthcoming paper (Schreiber *et al.* in prep.) we investigate if the SI can lead to diffusivities D or diffusion times t_{D} expressed in local orbits that can delay or even prohibit the collapse to planetesimals via internal diffusion of the clump. Since the dust-to-gas density ratio ϵ will increase to very high numbers in the collapse phase, we will exceed ϵ-values previously investigated about several orders of magnitude, see Fig. 2 for our scanned parameter space. Our boxes range from $L = 0.1H$ down to $L = 0.001H$ and the ϵ values go from $\epsilon = 1$ up to $\epsilon = 1000$. Depending on the local gas density, which is a function of time and space within a protoplanetary disk, the Roche density can be reached at values of $\epsilon = 10 - 1000$. Our 3D simulations use typically several Mio. CPU hours per parameter set, which explains that scanning the necessary parameter space is a very expensive endeavour. We found that for increasing dust-to-gas ratios the SI was getting indeed a little weaker, but nevertheless did not die out (see Fig. 4).

4. Size prediction for planetesimals

The dust-to-gas ratio that corresponds to the local Roche density depends on the distance from the star as well as from the actual gas content of the disk as a function of the evolution of the disk. As a typical value we choose $\epsilon = 10$ at a distance of about 40 AU (= Astronomical Unit) from the central star. The measured diffusivities at the medium scale of $L = 0.01H$ is in dimensionless units around $D = 2.7 \times 10^{-6}$. This value for D can be plugged into our prediction for the planetesimal size a:

$$a \approx \frac{H/R}{0.03} \sqrt{\frac{D}{2.7 \times 10^{-6}}} \sqrt{\frac{0.1}{\mathrm{St}}} 88 \text{ km}. \tag{4.1}$$

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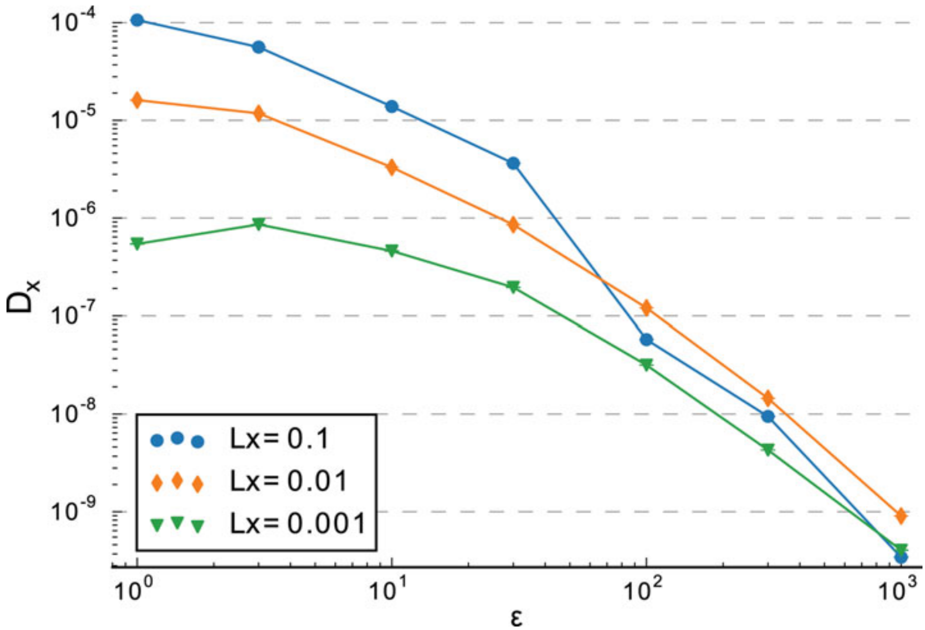

Figure 4. One of our results from our parameter study is a dust-to-gas ratio ϵ dependence of the diffusivity D. Here plotted is the radial diffusivity D_x for the parameter space study shown in Fig. 2. This is the input for our planetesimal collapse scenario and will give us the ability to calculate planetesimal properties, such as size and rate.

The resulting size is remarkably close to the measured sizes of the knee in the observed population of both asteroids and planetesimals and a nice support for our theory of planetesimal formation. An improved prediction of the actual gas content of the disk and the Stokes number of the available dust grains can still change the result, yet not by orders of magnitude. Johansen *et al.* (2012) and Johansen *et al.* (2015) already found typical initial planetesimal sizes (before pebble accretion) of 100-200km in agreement with our theory.

5. Outlook

Of course we have to refine our methods in several ways. For instance we have to study the streaming instability for other particle sizes (i.e., St) as well as for entire particle size distributions. We also have to study the effect of particle-particle collisions in a better way, as they will eventually start to dominate once we resolve the actual dimensions of the resulting planetesimal.

On the other hand we will surely test our ‘back of the envelope’ estimate for the criterion of planetesimal formation via straight forward 3D numerical simulations of streaming instability and gravitational collapse along the parameters as predicted from our non-self-gravitating runs. Then, a high resolution case of fully developed SI, as already obtained (see Fig. 3), will be the initial state for which we ‘simply’ have to switch on self-gravity and see A: Whether the box size allows for collapse, i.e., the unstable wavelength as determined from diffusivity and self gravity fits into the simulation domain. And B: Whether the resulting planetesimals obey our size prediction, hopefully independent on further increasing the resolution, i.e., reaching convergence with resolution for our simulations.

Then, we will be able to say how planetesimals in our solar system probably have formed and explain the size of asteroids and Kuiper belt objects.

After that, we can start investigating at what rate planetesimals were forming in the solar nebula. When did they form and at what distance from the star? Where did their building material come from? Which role do ices play? What kind of planetesimals did form the earth and does it help us to understand the chemical composition of the earth?

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References

Asphaug, E. & Benz, W. (1996). Size, Density, and Structure of Comet Shoemaker-Levy 9 Inferred from the Physics of Tidal Breakup. *Icarus* 121, 225–248

ALMA Partnership, A., Brogan, C. L., Perez, L. M., Hunter, T. R., Dent, W. R. F., Hales, A. S., *et al.* (2015). The 2014 ALMA Long Baseline Campaign: First Results from High Angular Resolution Observations toward the HL Tau Region. *ApJ* (Letters) 808(1), L3, `http://doi.org/10.1088/2041-8205/808/1/L3`

Benisty, M., Juhasz, A., Boccaletti, A., Avenhaus, H., Milli, J., Thalmann, C., *et al.* (2015). Asymmetric features in the protoplanetary disk MWC 758. *A&A* 578, L6

Birnstiel, T., Klahr, H. & Ercolano, B. 2012. A simple model for the evolution of the dust population in protoplanetary disks. *A&A* 539, A148

Bottke, W. F., Durda, D. D., Nesvorny, D., Jedicke, R., Morbidelli, A., Vokrouhlicky, D., & Levison, H. F. (2005). Linking the collisional history of the main asteroid belt to its dynamical excitation and depletion. *Icarus*179(1), 63–94

Dittrich, K. (2013). Numerical Simulations of Planetesimal Formation in Protoplanetary Disks. *Uni Heidelberg, PhD-thesis* `http://www.ub.uni-heidelberg.de/archiv/15664`

Dittrich, K., Klahr, H., & Johansen, A. 2013. Gravoturbulent Planetesimal Formation: The Positive Effect of Long-lived Zonal Flows. *ApJ* (Letters) 763, 117

Flock, M., Ruge, J. P., Dzyurkevich, N., Henning, T., Klahr, H., & Wolf, S. 2015. Gaps, rings, and non-axisymmetric structures in protoplanetary disks. From simulations to ALMA observations. *A&A* 574, A68

Johansen, A., Klahr, H., & Henning, T. (2006). Gravoturbulent Formation of Planetesimals. *ApJ* 636, 1121–1134

Johansen, A., Oishi, J. S., Mac Low, M.-M., Klahr, H., Henning, T., & Youdin, A. (2007). Rapid planetesimal formation in turbulent circumstellar disks. *Nature* 448, 1022–1025

Johansen, A. & Youdin, A. 2007. Protoplanetary Disk Turbulence Driven by the Streaming Instability: Nonlinear Saturation and Particle Concentration. *ApJ* 662, 627–641

Johansen, A., Klahr, H., & Henning, T. (2011). High-resolution simulations of planetesimal formation in turbulent protoplanetary discs. *A&A* 529, A62

Johansen, A., Youdin, A. N., & Lithwick, Y. 2012. Adding particle collisions to the formation of asteroids and Kuiper belt objects via streaming instabilities. *A&A* 537, A125.

Johansen, A., Mac Low, M.-M., Lacerda, P., & Bizzarro, M. 2015. Growth of asteroids, planetary embryos, and Kuiper belt objects by chondrule accretion. *Science Advances* 1, 1500109.

Klahr, H. H. & Bodenheimer, P. 2003. Turbulence in Accretion Disks: Vorticity Generation and Angular Momentum Transport via the Global Baroclinic Instability. *ApJ* 582, 869–892

Nesvorny, D., Vokrouhlicky, D., Bottke, W. F., Noll, K., & Levison, H. F. (2011). Observed Binary Fraction Sets Limits on the Extent of Collisional Grinding in the Kuiper Belt. *ApJ* 141(5) ,159 http://doi.org/10.1088/0004-6256/141/5/159

Shariff, K. & Cuzzi, J. N. 2015. The Spherically Symmetric Gravitational Collapse of a Clump of Solids in a Gas. *ApJ* 805, 42

M. Stephan, J. Doctor, Jülich Supercomputing Centre. (2015). JUQUEEN: IBM Blue Gene/Q Supercomputer System at the Jülich Supercomputing Centre. Journal of large-scale research facilities, 1, A1. http://dx.doi.org/10.17815/jlsrf-1-18 http://doi.org/10.1016/j.icarus.2005.05.017

Youdin, A. & Johansen, A. 2007. Protoplanetary Disk Turbulence Driven by the Streaming Instability: Linear Evolution and Numerical Methods. *ApJ* 662, 613–626