# Summary

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[H2O Vapour 18](#_Toc485986788)

[2013 Podio 18](#_Toc485986789)

[WATER VAPOR IN THE PROTOPLANETARY DISK OF DG Tau 18](#_Toc485986790)

[water vapour detected in outer disk, where most water ice reservoirs are stored, Herschel observations, dominated by emission from envelope/outflow, strong UV radiation of parent star irradiates upper disk layer (heating to ≈ 600 K), suggest water delivery to terrestrial planets by impact of icy bodies forming in outer disk 18](#_Toc485986791)

[Ice 19](#_Toc485986792)

[2016 Deckers 19](#_Toc485986793)

[Collisions of solid ice in planetesimal formation 19](#_Toc485986794)

[collision experiments (water ice), cm projectiles on decimetre targets, 15 – 45 m/s, 255.8 K, disruptive sticking (low efficiency), upper threshold depends on projectile size (no mass transfer above that), near snowline evaporation and condensation expected to produce solid ice, free fall collisions (7 m/s, cm ice spheres, fragmentation threshold & COR) 19](#_Toc485986795)

[2016 Jost 19](#_Toc485986796)

[Experimental characterization of the opposition surge in fine-grained water–ice and high albedo ice analogs 19](#_Toc485986797)

[Characterisation experiments (bidirectional reflectance, VIS-NIR, surfaces built from small-grained spherical water-ice particles), results: coherent backscattering dominates for fresh samples, contribution decreases with increasing bulk porosity and particle shape irregularity, particle sintering (temporal effect), glory for granular surfaces formed by small particles, angular positon of glory depends on particle size 19](#_Toc485986798)

[2015 Fukazawa 20](#_Toc485986799)

[Properties of Ferroelectric Ice 20](#_Toc485986800)

[Characterisation (neutron diffraction, D2O with impurities (KOD, NaOD, LiOD, DCl, ND3, Ca(OD)2), atmospheric pressure) of “ferroelectric ice” (= ice XI, can generate giant electric fields), stable @ 57 – 74 K, can be important for planet formation, results: ferroelectric ice forms with dopants that produce L-defects (KOD, NaOD), no ferroelectricity observed for samples with D-defect 20](#_Toc485986801)

[2015 Gundlach 20](#_Toc485986802)

[The stickiness of micrometer-sized water-ice particles 20](#_Toc485986803)

[Collision experiments (μm-sized ice particles growing aggregates, 114 – 260 K), results: threshold velocity for sticking: 9.6 m/s below 210 K, increasing with T above 210 K, threshold velocity ≈ 10 x larger than for μm-sized silica particles, erosion of aggregates: v > 15.3 m/s, specific surface energy, viscous relaxation time 20](#_Toc485986804)

[2015 Hill 20](#_Toc485986805)

[Collisions of small ice particles under microgravity conditions 21](#_Toc485986806)

[II. Does the chemical composition of the ice change the collisional properties? 21](#_Toc485986807)

[Collision experiments (1.5 cm ice spheres (pure / 5 % methanol / 5 % formic acid), 0.01 – 0.19 m/s, 131 – 160 K, 10-5 mbar), results: range of COR values, no correlation to chemical composition / velocity / temperature, surface roughness is dominant factor in explaining range of COR 21](#_Toc485986808)

[2014 Hill 21](#_Toc485986809)

[Collisions of small ice particles under microgravity conditions 21](#_Toc485986810)

[Collision experiments (microgravity, icy particles (4.7 – 10.8 mm diameter, spherical or irregular fragments), 0.27 – 0.51 m/s, 131 – 160 K) colliding with each other, impact parameters: 0 - 1), results: mostly bouncing, few cases of fragmentation, COR evenly spread between 0.08 – 0.65 (average 0.36), ≥ 58 % translational energy lost, ≤ 17 % translational converted to rotational energy, COR not affected by temperature 21](#_Toc485986811)

[2014 Yasui 22](#_Toc485986812)

[Impact strength of small icy bodies that experienced multiple collisions 22](#_Toc485986813)

[Collision experiments (multiple impacts, polycrystalline target, cylindrical projectile, 258 – 263 K, 84 – 502 m/s), results: impact strength: 77.6 J/kg, number of fine fragments depends on energy density at collision -> crater size distribution of Phoebe (Saturnian icy satellite), impact velocity dependence 22](#_Toc485986814)

[2014 Aumatell 22](#_Toc485986815)

[Ice aggregate contacts at the nm-scale 22](#_Toc485986816)

[Experiments (nm ice particles), thermal gradient force microscope (measure pull-off forces/twisting torques), ice aggregates in astrophysical settings more robust against restructuring than originally thought, likely grow as fractal aggregates to larger size before they restructure, retain high porosity 22](#_Toc485986817)

[2012 Shimaki 23](#_Toc485986818)

[Low-velocity collisions between centimeter-sized snowballs: Porosity dependence of coefficient of restitution for ice aggregates analogues in the Solar System 23](#_Toc485986819)

[Collision experiments (free-fall, cm-size, sintered snowballs, 44 – 80 % porosity, impact velocity: 0.44 – 4.12 m/s, 263 K), sticking dominant for porosity > 70 %, else bouncing dominant, COR depends strongly on porosity rather than velocity, decrease with increasing porosity, dynamic compressive strength of snow measure from impact compaction (consistent with upper limit of static compressive strength, analysis of collisions using Johnson’s model 23](#_Toc485986820)

[2012 Shimaki 23](#_Toc485986821)

[Experimental study on collisional disruption of highly porous icy bodies 23](#_Toc485986822)

[Collision experiments (sintered porous ice spheres on targets, porosity 40 – 70 %, 2.4 – 489 m/s), results: sticking above threshold velocity (porosity dependent: decreasing with increasing velocity, 44 m/s @ 60 %, 13 m/s @ 70 %), shattering strength of target decreases with increasing porosity (100 j/kg @ 40 %, 31 J/kg @ 70 %), antipodal velocity increased with increasing energy density and porosity, fragment mass distribution depends on porosity and energy density 23](#_Toc485986823)

[2010 Schegerer 24](#_Toc485986824)

[Spatially resolved detection of crystallized water ice in a T Tauri object 24](#_Toc485986825)

[spectroscopic detection of crystalline water ice in young stellar object, predominantly small grains (0.1 – 0.3 μm), few large grains, evidence for grain growth, crystallinity increases in upper layers of circumstellar disk, only amorphous grains exist in bipolar envelope, crystallization close to disk atmosphere, where water ice is shielded from hard radiation 24](#_Toc485986826)

[2010 Heißelmann 24](#_Toc485986827)

[Microgravity experiments on the collisional behavior of saturnian ring particles 24](#_Toc485986828)

[Collision experiments (microgravity), I. parabolic flight (1.5 cm spheres, 6 – 22 cm/s, cryogenic temperatures), results: uniform distribution of COR between 0.06 – 0.84 (0.45 mean), II. mini lab drop tower (ensemble of cm-sized glass beads), results: kinetic energy development of system can be described by granular fluid model (Haff’s law) with a constant COR of 0.64, setup suitable for velocities ≤ 5 mm/s 24](#_Toc485986829)

[2010 Zamankhan 25](#_Toc485986830)

[Simulations of collision of ice particles 25](#_Toc485986831)

[develop realistic model for ice-structure interaction, analysis of Bridges 1984 ice ball experiments, difficult to predict onset of fragmentation/fracturing, most energy dissipation is result of racturing at contact surface, questions validity of constitutive models (e.g. Brilliantov/Hertzsch) 25](#_Toc485986832)

[2007 Schäfer 25](#_Toc485986833)

[Collisions between equal-sized ice grain agglomerates 25](#_Toc485986834)

[numerical study, collisional outcome of low velocity impacts, equal sized porous agglomerates (too large for lab experiments), growth for head-on collisions seems possible, but very little sticking for most material strengths, rotation for glancing collisions, no significant compaction for low velocity impacts 25](#_Toc485986835)

[2005 Wang 26](#_Toc485986836)

[STICKY ICE GRAINS AID PLANET FORMATION: UNUSUAL PROPERTIES OF CRYOGENIC WATER ICE 26](#_Toc485986837)

[Experiments, vapour deposited amorphous water ice (5 – 100 K), sticking, ≈ 10 % bouncing 26](#_Toc485986838)

[2004 Austen Angell 26](#_Toc485986839)

[AMORPHOUS WATER 26](#_Toc485986840)

[ASW, characterization and production of different amorphous and glassy phases, glass transition, polyamorphicity 26](#_Toc485986841)

[2003 Flin 27](#_Toc485986842)

[Full three-dimensional modelling of curvature-dependent snow metamorphism: first results and comparison with experimental tomographic data 27](#_Toc485986843)

[Numerical modelling (snow metamorphism, near 0°C), structure changes driven by temperature and humidity fields, high vapour pressure => metamorphism in first approximation curvature driven (neglecting crystallographic and diffusion-limited effects), basic equations: Kelvin & Langmuir-Knudsen, result: analytical growth law of ice phase 27](#_Toc485986844)

[2002 Hertzsch 27](#_Toc485986845)

[A model for surface effects in slow collisions of icy grains 27](#_Toc485986846)

[numerical model, slow collisions, solid grains, planar motion, elasticity + viscosity + soft surface layers + adhesion + friction, COR components, water ice (cm size), critical velocity (bouncing sets in) 27](#_Toc485986847)

[1999 Arakawa 28](#_Toc485986848)

[Ejection velocities of ice fragments in oblique impacts of ice spheres 28](#_Toc485986849)

[Collision experiments (-18°C, 170 – 640 m/s, ice spheres colliding), results: minimum ejection velocity decreases with increasing impact angle and increases with increasing specific energy (kinetic energy of projectile normalised to target mass), maximum ejecta velocity independent of impact angle and velocity, icy planets > 100 km radius can capture most fragments from collisions between 0 – 50° 28](#_Toc485986850)

[1999 Ryan 28](#_Toc485986851)

[A Laboratory Impact Study of Simulated Edgeworth–Kuiper Belt Objects 28](#_Toc485986852)

[Collision experiments (low-velocity airgun shots, target: porous/homogeneous ice spheres, projectile: aluminium/solid ice/fractured ice), results: porous targets as strong as solid targets (voids dissipate energy well), but aluminium projectile more damaging than solid ice, solid ice more damaging than fractured ice (lower penetration depth => less energy coupled into target), impact strength (porous targets impacted by porous/solid projectiles) > 5 x 105 erg/cm3 28](#_Toc485986853)

[1999 Arakawa 29](#_Toc485986854)

[Collisional Disruption of Ice by High-Velocity Impact 29](#_Toc485986855)

[Collision experiments (high velocity (2.3 – 4.7 km/s), -10°C, cubic ice targets (15 – 100 mm), nylon projectile (7 mg), mass ratio projectile/target: 10-6 – 10-3), results: shock pressure attenuates as (projectile size/propagation distance)2, irrespective of mass ratio, reaccumulation and escape conditions: large (radius > 20 k) icy bodies will reaccumulate and form rubble pile, small (radius < 2 km) icy bodies will never reaccumulate after catastrophic disruption (all fragments escape) 29](#_Toc485986856)

[1998 Iedema 29](#_Toc485986857)

[Ferroelectricity in Water Ice 29](#_Toc485986858)

[Characterisation experiments (partially proton-ordered ice Ic (vapour deposited on Pt(111) substrate), 40 – 150 K, Kelvin probe), result: slight preference for O aiming away from surface, 0.2 % net dipole per H2O molecule (@ 40 K) = -3 mV/monolayer, decreases with deposition T (exp(-T/27K)), when ice changes from amorphous to crystalline (130, 140, 150 K), dielectric properties become active, vapour-deposited ice in space may develop large electric fields 29](#_Toc485986859)

[1998 Higa 30](#_Toc485986860)

[Size Dependence of Restitution Coefficients of Ice in Relation to Collision Strength 30](#_Toc485986861)

[size dependence of COR, water ice spheres (1.4 – 36 mm), 1 – 1000 cm/s, 261 K, critical velocity 30](#_Toc485986862)

[1997 Supulver 30](#_Toc485986863)

[The Sticking Properties of Water Frost Produced under Various Ambient Conditions 30](#_Toc485986864)

[water frost sticking properties, thin porous frost stickier than thick dense frost, temperature fluctuations increase stickiness, frost bond elastic (like spring), they suggest frost to be in proto-planetary nebulae 30](#_Toc485986865)

[1996 Dilley 31](#_Toc485986866)

[Mass dependence of energy loss in collisions of icy spheres: An experimental study 31](#_Toc485986867)

[collision experiments, ice spheres with ice blocks, ≈ 250 K, collisions become inelastic < 1 cm/s, elasticity decreases with decreasing mass 31](#_Toc485986868)

[1996 Bridges 31](#_Toc485986869)

[Energy Loss and Sticking Mechanisms in Particle Aggregation in Planetesimal Formation 31](#_Toc485986870)

[Contact sticking experiments (surfaces coated with different types of frost, deposited at various low T and p) results: several frost coated surfaces stick together when brought into contact at ≈ 100 K, sticking force depends on deposition conditions, ice particles covered with H2O/CO2: sticking at low impact velocities, energy loss depends on v and surfaces structure, CH3OH: also effective sticky frost 31](#_Toc485986871)

[1996 Higa 31](#_Toc485986872)

[Measurements of restitution coefficients of ice at low temperatures 32](#_Toc485986873)

[COR const. (0.88), ice spheres 1.5 cm, 1 – 700 cm/s, 113 – 269 K 32](#_Toc485986874)

[1996 Arakawa 32](#_Toc485986875)

[Measurements of ejection velocities in collisional disruption of ice spheres 32](#_Toc485986876)

[Collision experiments (ice spheres (projectile: 1.5 g, target: 1.5, 12, 172 g), reaccumulation, -18°C, 150 – 690 m/s), results: ejection velocity varies with initial position (3 – 110 x impact velocity), antipodal velocity varies with distance from impact point and with specific energy (1.7 – 2.9 x impact velocity) 32](#_Toc485986877)

[1995 Arakawa 32](#_Toc485986878)

[Ejection Velocity of Ice Impact Fragments 32](#_Toc485986879)

[Collison experiments (ice, projectile on target impact, 30 – 530 m/s, mass ratio p/t = 0.1 to 0.0035), results: energy density (ice target begins to break up at 83 J/kg (5 times smaller than for basalt)), fragmentation strength, ejection velocity (2 times higher than for basalt), impact stress (decay constant decreases with increasing impact velocity) 32](#_Toc485986880)

[1995 Kato 33](#_Toc485986881)

[Ice-on-Ice Impact Experiments 33](#_Toc485986882)

[Collision experiments (cratering & fragmentation, vertical gas gun, 255 K, projectiles: ice/aluminum, polycarbonate), results: mass distribution of fragments (power law, ice exponent bigger than for rock collisions, the same as found in Saturn’s rings => they probably originate from collisional disruption) 33](#_Toc485986883)

[1995 Supulver 33](#_Toc485986884)

[The coefficient of restitution of ice particles in glancing collisions: Experimental results for unfrosted surfaces 33](#_Toc485986885)

[Saturn’s rings, planetesimals disc, glancing collisions, COR components, spherical ice ball on long period pendulum, flat ice surface target, 100 K, smooth ice surface, room temperature collisions of rubber ball on rough surface (tangential friction force, highest energy loss at 45°-60° impact angle) 33](#_Toc485986886)

[1991 Hatzes 34](#_Toc485986887)

[Coagulation of Particles in Saturn's Rings: Measurements of the Cohesive Force of Water Frost 34](#_Toc485986888)

[Collision experiments (sticking of frosted ice particles, frost layer 10 – 100 μm), results: no frost: cohesion force < 1 dyn, frost: cohesion force ≤ 100 dyn, dependent on impact velocity, cohesion maximal for intermediate v (≈ 0.1 cm/s), decreasing for smaller or larger velocities, spring constant of bond: 104 dyn, range of bond: 10 μm => ice particles should be able to survive tidal disruption when < 10 m 34](#_Toc485986889)

[1989 McDonald 34](#_Toc485986890)

[Mass transfer during ice particle collisions in planetary rings 34](#_Toc485986891)

[Collision experiments (lab), result: 5 % of mass are exchanged, less than that are transferred 34](#_Toc485986892)

[1989 Hallbrucker 34](#_Toc485986893)

[The heat capacity and glass transition of hyperquenched glassy water 35](#_Toc485986894)

[differential scanning calorimetry, 103 – 273 K, thermally reversible glass-liquid transition (Tg = 136 K, activation energy of structural relaxation ≈ 55 kJ/mol, transition width 12 K, increase in heat capacity = 1.6 kJ/mol), liquid water forms from glassy water at 146 K, crystallization near 232 K 35](#_Toc485986895)

[1988 Hatzes 35](#_Toc485986896)

[Collisional properties of ice spheres at low impact velocities 35](#_Toc485986897)

[experiments, water ice spheres, disc pendulum, 85 K, 10-5 torr, COR:ε(v)= C exp (−γv), 0.015 – 2 cm/s, COR lowered by 10 – 30 % if surface rough/frosted, frost changes COR from exponential to power-law behaviour, application of results to Saturn’s rings 35](#_Toc485986898)

[1987 Lange 35](#_Toc485986899)

[Impact Experiments in Low-Temperature Ice 36](#_Toc485986900)

[Collision experiments (cubic & cylindrical ice targets (20 cm), 81 & 257 K, 100 – 640 m/s), results: crater diameters: 7 – 15 cm (2 – 3 x larger than for basalt at same conditions, 10 – 100 x larger than for crystalline rock), craters increase slightly with increasing target temperature 36](#_Toc485986901)

[1984 Bridges 36](#_Toc485986902)

[Structure, stability and evolution of Saturn’s rings 36](#_Toc485986903)

[experiment results, COR of icy particles, Voyager spacecraft results, thickness of Saturn’s rings < 150 m, several ringlets (few m – 10 km radial dimension), some unstable to viscous diffusion -> optical depth variations 36](#_Toc485986904)

[1983 Maeno 36](#_Toc485986905)

[Pressure sintering of ice and its implication to the densification of snow at polar glaciers and ice sheets 36](#_Toc485986906)

[Sintering experiments, six or more mechanisms contributing to neck growth simultaneously, review of pressureless sintering processes (vapour transport dominating, surface diffusion important in early stages), densification of snow = pressure sintering (takes into account three diffusional and dislocation creep mechanisms) 36](#_Toc485986907)

[1982 Mayer 37](#_Toc485986908)

[Vitrification of pure liquid water by high pressure jet freezing 37](#_Toc485986909)

[produce vitrified (=glassy) water in a jet, compare X-ray diffraction patterns to vapour deposited ASW 37](#_Toc485986910)

[1982 Kuroda 37](#_Toc485986911)

[Growth kinetics of ice from the vapour phase and its growth forms 37](#_Toc485986912)

[Theory, ice growing from vapour deposition, changes with temperature, -35°C – -4°C, vapour – quasi-liquid – solid mechanism / adhesive growth / 2D nucleation growth, type of surface structure (and thus growth mechanism) depends on surface orientation ({0001} or {1010} face) and temperature, spherical volume diffusion field near {0001} face, cylindrical volume diffusion field near {1010} face, surface diffusion from {0001} to {1010} faces 37](#_Toc485986913)

[1964 Hobbs 38](#_Toc485986914)

[The Sintering and Adhesion of Ice 38](#_Toc485986915)

[characterisation experiments (sintering (single and polycrystalline ice spheres (50 – 700 μm diameter), -3 – -20°C ), in air/hydrogen-gas/oil), results: evaporation-condensation theory valid (diffusion through environmental gas enhances neck growth), no evidence of liquid-like surface layer found unless surfaces are contaminated (e.g. by salts) 38](#_Toc485986916)

[1961 Kuroiwa 38](#_Toc485986917)

[A Study of Ice Sintering 38](#_Toc485986918)

[Characterization experiments (sintering (ice spheres < 200 µm diameter), in saturated air/kerosene environments), results: neck growth rate, ice-bonding (adhesion) is result of solid diffusion 38](#_Toc485986919)

[Dust + Ice 39](#_Toc485986920)

[2017 Sirono 39](#_Toc485986921)

[Collisions between Sintered Icy Aggregates 39](#_Toc485986922)

[Numerical simulation: collisions of sintered icy dust aggregates, including temperature induced growth of sinter necks. Results: sintering strongly affects collisional growth, porous aggregates: critical velocity for growth 20 m/s (non-sintered 50 m/s), compact aggregates: main outcome is bouncing 39](#_Toc485986923)

[2015 Lorek 39](#_Toc485986924)

[Compaction of ice pebbles in collapsing pebble clouds and the dust-to-ice ratio of comets 39](#_Toc485986925)

[Numerical model for comet formation (gravitational collapse of pebble (ice & silica) clouds, streaming instability), results: dust-to-ice ratio estimates for cometesimals 39](#_Toc485986926)

[2014 Johansen 39](#_Toc485986927)

[The multifaceted planetesimal formation process 39](#_Toc485986928)

[hybrid model for planetesimal formation (particle growth starts unaided by self-gravity but later proceeds inside gravitationally collapsing pebble clumps to form planetesimals with a wide range of sizes) 39](#_Toc485986929)

[2014 Blum 40](#_Toc485986930)

[Comets formed in solar-nebula instabilities! – An experimental and modeling attempt to relate the activity of comets to their formation process 40](#_Toc485986931)

[Modelling and experiments on dust emission from comets etc., homogeneous layers of μm sized dust particles reach tensile strengths (103 – 104 Pa) far higher than water’s sublimation pressure, model of formation by gravitational instability leads to tensile strength of 1 Pa instead => could explain water driven comet activity (minimum size for dust-aggregates: ≈ 1 mm) => cometesimals must have formed by gravitational instability 40](#_Toc485986932)

[2014 Testi 40](#_Toc485986933)

[Dust Evolution in Protoplanetary Disks 41](#_Toc485986934)

[Review: core accretion scenario, dust aggregate growth, last critical stages must happen in dense mid-plane -> observations at sub-mm – cm wavelengths required (ALMA), collision constraints (lab & modelling), dust settling, radial transport, global dust evolution models, migration/fragmentation barrier 41](#_Toc485986935)

[2013 Wada 41](#_Toc485986936)

[Growth efficiency of dust aggregates through collisions with high mass ratios 42](#_Toc485986937)

[Numerical simulation (collisions of different-sized icy dust aggregates), growth efficiency for nearly head-on collisions increases with size, growth efficiency increases with increasing mass ratio of colliding aggregates, growth possible at several 10 m/s for icy dust 42](#_Toc485986938)

[2013 Kataoka 42](#_Toc485986939)

[Fluffy dust forms icy planetesimals by static compression 42](#_Toc485986940)

[analytical analysis of static compression (disk gas pressure and self gravity), coagulation forms fluffy grains, problem: collisions don’t compress them enough to from compact planetesimals, gas and self gravity can overcome this 42](#_Toc485986941)

[2013 Ros 43](#_Toc485986942)

[Ice condensation as a planet formation mechanism 43](#_Toc485986943)

[numerical modeling, condensation (around snow line) can support/continue growth where dust coagulation is frustrated by barriers, growth from mm to decimeter scale in 1000 years, water transport over radial ice line dominant (over atmospheric ice line negligible), model ignores sticking/fragmenting particle collisions 43](#_Toc485986944)

[2012 Suyama 43](#_Toc485986945)

[GEOMETRIC CROSS SECTIONS OF DUST AGGREGATES AND A COMPRESSION MODEL FOR AGGREGATE COLLISIONS 43](#_Toc485986946)

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[2012 Okuzumi 44](#_Toc485986948)

[RAPID COAGULATION OF POROUS DUST AGGREGATES OUTSIDE THE SNOW LINE: A PATHWAY TO SUCCESSFUL ICY PLANETESIMAL FORMATION 44](#_Toc485986949)

[Model simulations (porosity change, submicron-sized icy dust aggregates, neglect fragmentation), result: internal densities << 0.1 g/cm3, overcome radial drift barrier at orbital radii < 10 AU 44](#_Toc485986950)

[2011 Aumatell 44](#_Toc485986951)

[Breaking the ice: planetesimal formation at the snowline 44](#_Toc485986952)

[Lab experiments, sublimation of freely levitating ice aggregates, frequent break up, sublimation of drifting ice aggregates might locally increase the density of small dust (silicate) 44](#_Toc485986953)

[2011 Gundlach 45](#_Toc485986954)

[Micrometer-sized ice particles for planetary-science experiments – 45](#_Toc485986955)

[I. Preparation, critical rolling friction force, and specific surface energy 45](#_Toc485986956)

[Characterisation of ice aggregates, built of μm-sized H2O ice particles (formed by spraying water into liquid N2), porosity of aggregates depends on production method: 0.11 – 0.72 volume filing factor, critical rolling friction force ice: 114.8 x 10-10 N (silica: 12.1 x 10-10 N), adhesive bonding for ice stronger than for SiO2, specific surface energy ice: 0.19 J/m2 45](#_Toc485986957)

[2011 Sirono 45](#_Toc485986958)

[THE SINTERING REGION OF ICY DUST AGGREGATES IN A PROTOPLANETARY NEBULA 45](#_Toc485986959)

[Sintering increases strength of neck in aggregates, sintering region can span whole nebula 45](#_Toc485986960)

[2011 Sirono 45](#_Toc485986961)

[Planetesimal formation induced by sintering 46](#_Toc485986962)

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[2011 Saito 46](#_Toc485986964)

[Planetesimal formation by sublimation 46](#_Toc485986965)

[Modelling (infall of icy dust aggregates by gas drag => temperature increase => H2O sublimation inside snow line => ejection of silicate cores (slower infall than icy dust => accumulation => gravitational instability) 46](#_Toc485986966)

[2010 Min 46](#_Toc485986967)

[The thermal structure and the location of the snow line in the protosolar nebula: axisymmetric models with full 3-D radiative transfer 46](#_Toc485986968)

[modeling H2O snowline in young solar nebula (optically thick), two opposite effects (shielding/viscous heating), snowline position sensitive to dust grain opacity/mass accretion rate of disk, compute abundances of ice/dust, jump in solid surface density at snowline (and where rocky planets formed) smaller than previously assumed 46](#_Toc485986969)

[2009 Salter 47](#_Toc485986970)

[A zero-gravity instrument to study low velocity collisions of fragile particles at low temperatures 47](#_Toc485986971)

[Collision experiments (microgravity (parabolic flight),, 0.03 – 0.28 m/s, 80 – 300 K), instrument description 47](#_Toc485986972)

[2009 Yasui 47](#_Toc485986973)

[Compaction experiments on ice-silica particle mixtures: Implication for residual porosity of small icy bodies 47](#_Toc485986974)

[Compaction experiments (ice-silica mix, silica volume fractions 0 – 0.29, constant compression speed (0.2 / 2.0 mm/min), 263 K (30 MPa max compaction pressure) or 206 – 218 K (80 MPa max compaction pressure)), results: residual porosity larger for higher silica fractions (0.01 – 0.14 @(263 K & 30 MPa), 2 – 10 times larger @(206 – 218 K & 80 MPa)), model: predicts icy bodies < 700 km diameter to have residual porosity > 0.3 for T < 218 K. 47](#_Toc485986975)

[2008 Blum 48](#_Toc485986976)

[The Growth Mechanisms of Macroscopic Bodies in Protoplanetary Disks 48](#_Toc485986977)

[Review of experimental achievements in context with protoplanetary disks, planetesimal formation: growth of fractal dust aggregates -> compaction -> mean velocity increases with increasing aggregate size -> stalling of growth / possible fragmentation (@ dm-sizes), hypotheses for further growth: sticky materials, secondary collision processes, enhanced growth at snow-line, cumulative dust effects, gravitational instability. 48](#_Toc485986978)

[2008 Suyama 48](#_Toc485986979)

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[2007 Heißelmann 49](#_Toc485986983)

[Experimental Studies on the Aggregation Properties of Ice and Dust in Planet-Forming Regions 49](#_Toc485986984)

[Collision experiments (microgravity (parabolic flight), 0.1 – 0.5 m/s, dust / ice), instrument description, results: mostly bouncing, translational energy loss ≈ 95 % 49](#_Toc485986985)

[2004 Arakawa 49](#_Toc485986986)

[Ice–silicate fractionation among icy bodies due to the difference of impact strength between ice and ice–silicate mixture 49](#_Toc485986987)

[Collision experiments (impact disruption of ice-silicate mixtures, silicate mass ratio 0 – 0.5, porosities: 0 – 37 %, 150 – 670 m/s), results: impact strength decreases with increasing porosity (mixture) / increases with porosity (pure H2O), higher silicate ratios enhanced strength 49](#_Toc485986988)

[2003 Ehrenfreund 49](#_Toc485986989)

[Physics and chemistry of icy particles in the universe: answers from microgravity 50](#_Toc485986990)

[cold ISM: dust particles covered in ultrathin icy layers, drive rich chemistry in star-forming regions, polar caps of terrestrial planets and outer solar system satellites covered in ice, earth atmosphere, weather etc., are lab ices good analogues?, bulk structure, surface catalytic properties, ice + dust experiments (1 + 0 g) + models, proposed experiments for ISS 50](#_Toc485986991)

[2002 Arakawa 50](#_Toc485986992)

[Impact Experiments on Porous Icy-Silicate Cylindrical Blocks and the Implication for Disruption and Accumulation of Small Icy Bodies 50](#_Toc485986993)

[Collision experiments (pure ice & ice-silica mix, porosity ≤ 55 %, 150 – 670 m/s, 263 K), results: maximum ejecta velocity (normalized by impact velocity) decreases with increasing porosity & is independent of material (mix), impact strength: pure ice: increase with increasing porosity, mixture: decrease with increasing porosity, three types of collisional outcome: mass loss, rubble pile formation, regolith formation (compaction) 50](#_Toc485986994)

[1997 Dominik 51](#_Toc485986995)

[The physics of dust coagulation and the structure of dust aggregates in space 51](#_Toc485986996)

[Modelling (collisions of dust, ice + other materials), results: growth of aggregates by monomers normally not restructures them, hit-and-stick assumption reasonably valid, significant compaction in aggregate collisions, critical energies for different restructuring processes (help modelling), turbulence compresses aggregates 51](#_Toc485986997)

[1997 Weidenschilling 51](#_Toc485986998)

[The Origin of Comets in the Solar Nebula: A Unified Model 51](#_Toc485986999)

[Modelling (numerical simulation (growth of cometesimals), beginning with uniform mixture of microscopic grains in nebular gas, coagulation, settling => small aggregates in central plane, gas drag, radial motion, velocity dispersion prevents gravitational instability to grow bodies > 10 m), results: size-distribution of cometesimals shows narrow peak @ 10’s – 100’s m, resulting bodies have low mechanical strength, macroscopic voids, small scale porosity 51](#_Toc485987000)

[1993 Weidenschilling 52](#_Toc485987001)

[Formation of planetesimals in the solar nebula 52](#_Toc485987002)

[Book chapter (evolution of solid particles in solar nebula), bodies ≤ km: motion dominated by gas drag, planetesimals probably formed by coagulation of grain aggregates, collisions caused by differential settling, turbulence, gas drag, orbital decay, sticking mechanisms poorly understood, growth aided by concentration of larger bodies toward central plane, gravitational instability unlikely for particle layer formed by settling (turbulence prevents reaching critical density (independent of particle size) 52](#_Toc485987003)

[1983 Lange 52](#_Toc485987004)

[The dynamic tensile strength of ice and ice-silicate mixtures 53](#_Toc485987005)

[Characterization experiments (strain rate and dynamic tensile strength of ice and ice-silicate mixtures), results: strengths vary between 1.6 – 22 MPa, strength increases with increasing silicate content and with applied strain rate (10-2 – 104 s-1), strength-strain relation similar to other geological materials 53](#_Toc485987006)

[Dust 54](#_Toc485987007)

[2014 Deckers 54](#_Toc485987008)

[Macroscopic dust in protoplanetary disks – from growth to destruction 54](#_Toc485987009)

[Collisions experiments (small drop tower, p < 0.5 mbar, 6.68 m/s, agglomerates of quartz dust (irregularly shaped μm-sized grains), cm-sized projectile (volume filling factor 0.466, varying height, diameter, mass), dm-sized target (1.5 kg, 12 cm diameter and height, volume filling factor 0.44)), results: low collision energies: mass transfer to target, projectile destroyed, accretion efficiency decreasing with increasing obliquity and increasing difference in filling factor (projectile more compact than target), accretion efficiency increases with increasing collision energy until threshold (298 mJ), beyond threshold: catastrophic disruption of target -> critical fragmentation strength: 190 mJ/kg (larger than expected), mass distribution of fragments: more small fragments for higher collision energies, implication for planet formation: smaller particles couple better to gas-drag -> re-accretion more likely 54](#_Toc485987010)

[2014 Blum 54](#_Toc485987011)

[Laboratory Drop Towers for the Experimental Simulation of Dust-aggregate Collisions in the Early Solar System 54](#_Toc485987012)

[Collision experiments (description of lab dropt towers for dust (≤ 10 cm, ≤ 70 % porosity) collisions (0.01 m/s ≤ v ≤ 10 m/s)) 54](#_Toc485987013)

[2014 Kelling 55](#_Toc485987014)

[EXPERIMENTAL STUDY ON BOUNCING BARRIERS IN PROTOPLANETARY DISKS 55](#_Toc485987015)

[Long term lab experiments, interaction of 100 dust aggregated with each other (1 mm, mm/s – cm/s, 900 s duration, 105 collisions, 2000 analysed), sticking and fragmentation, no net growth, bouncing barrier is likely limit of self-consistent particle growth 55](#_Toc485987016)

[2013 Seizinger 55](#_Toc485987017)

[Erosion of dust aggregates 55](#_Toc485987018)

[model (molecular dynamics, spherical grain interactions, visco-elastic damping force, different sample generation methods), visco-elastic damping crucial to reproduce lab-results, erosion at impact velocities > 5 m/s, compact aggregates harder to erode, increasing projectile size shifts erosion threshold to higher velocities 55](#_Toc485987019)

[2013 Meisner 56](#_Toc485987020)

[Preplanetary scavengers: Growing tall in dust collisions 56](#_Toc485987021)

[lab experiments, self-consistent evolution of dust target under continuous impact of sub-mm dust aggregates (71 m/s) -> mass gain of target, accretion efficiency decreasing with increasing velocity, projectile-mass dependent, target volume filling factor stabilizes at 38 %, large bodies can grow further by sweeping up smaller ones (high efficiency) 56](#_Toc485987022)

[2013 Hirashita 56](#_Toc485987023)

[Condition for the formation of micron-sized dust grains in dense molecular cloud cores 56](#_Toc485987024)

[Numerical modelling (formation of μm-sized grains in dense cores of molecular clouds), results: coreshine (mid-IR emission due to scattering from μm-sized grains in dense cores) must come from long-lived entities rather than dynamically transient objects (based on free-fall time for typical hydrogen densities around 105 cm-3) 56](#_Toc485987025)

[2013 Kothe 57](#_Toc485987026)

[Free collisions in a microgravity many-particle experiment. 57](#_Toc485987027)

[III. The collision behavior of sub-millimeter-sized dust aggregates 57](#_Toc485987028)

[microgravity experiments, collisions of sub-mm dust agglomerates (from m monomer grains), internal structure studied by X-ray CT before experiments -> no rim compaction -> no preparation artifacts, shallow power-law relation between aggregate mass and bouncing barrier velocity, no sharp transition sticking/bouncing, aggregates-of-aggregates stick at higher velocities than homogeneous agglomerates 57](#_Toc485987029)

[2013 Garaud 57](#_Toc485987030)

[FROM DUST TO PLANETESIMALS: AN IMPROVED MODEL FOR COLLISIONAL GROWTH IN PROTOPLANETARY DISKS 57](#_Toc485987031)

[modelling, velocity distribution includes deterministic motion (from the vertical settling, radial drift, and azimuthal drift) and stochastic motion (from Brownian motion and turbulence), suggest they can thereby overcome bouncing barrier, grow large planetesimals and keep up significant population of small (m) grains 57](#_Toc485987032)

[2012 Tanaka 58](#_Toc485987033)

[Growth of Cosmic Dust Aggregates and Re-examination of Particle Interaction Models 58](#_Toc485987034)

[molecular dynamics simulation of particle collisions, dust growth 58](#_Toc485987035)

[2012 Schräpler 58](#_Toc485987036)

[The physics of protoplanetesimal dust agglomerates. 58](#_Toc485987037)

[VII. The low-velocity collision behaviour of large dust agglomerates 58](#_Toc485987038)

[Microgravity collision experiments (macroscopically homogeneous dust agglomerates of μm-sized silica particles, volume filling factors: 0.3 & 0.4, size: 5 cm, impact velocities: 0.01 – 0.5 m/s), COR + fragmentation velocity measured, ε(v): low v – ε decreases with increasing v, then constant, then onset of fragmentation, interpretation: transition from solid-body-dominated to granular-medium-dominated behaviour, molecular dynamics simulation to model experimental results, extension of earlier work (improved measurements, better statistics, theoretical approach), applications: protoplanetary disks, debris disks, planetary rings 58](#_Toc485987039)

[2012 Windmark 59](#_Toc485987040)

[Breaking through: The effects of a velocity distribution on barriers to dust growth 59](#_Toc485987041)

[model, dust growth, effect of probability distribution on growth barriers (bouncing/fragmentation) -> barriers not sharp, small fraction of particles manage to grow orders of magnitude above the main population, velocity distribution softens fragmentation barrier + removes bouncing barrier, broadens size distribution -> seeds for sweep-up 59](#_Toc485987042)

[2012 Seizinger 59](#_Toc485987043)

[Compression behavior of porous dust agglomerates 59](#_Toc485987044)

[Modelling (molecular dynamics approach to include normal forces, rolling, twisting and sliding between dust grains), aim: improve model for interaction of individual monomers to determine threshold between growth and destruction 59](#_Toc485987045)

[2012 Windmark 60](#_Toc485987046)

[Planetesimal formation by sweep-up: how the bouncing barrier can be beneficial to growth 60](#_Toc485987047)

[dust collision model based on lab experiments (fragmentation with mass transfer -> growth at high impact velocities), cratering + mass transfer, smooth transition from equal to different-sized collisions, few cm-sized grains can act as catalyst for sticking and sweep up smaller particles (3 AU -> 100 m sized objects form in 1 Myr), bouncing barrier in this scenario beneficial (prevents growth of too many cm sized particles, maintains reservoir of small ones to be swept up), BUT few cm-sized particles have to be produced somehow to start with 60](#_Toc485987048)

[2012 Perry 61](#_Toc485987049)

[The influence of monomer shape on aggregate morphology 61](#_Toc485987050)

[influence of monomer shape (prolate ellipsoidal/spherical) on morphology of dust aggregates, particle-cluster aggregation vs. cluster-cluster aggregation, shape and aggregation mechanism influence compactness (8 – 80 %) and friction times, aggregates of spherical particles may not be good analogues for ISM dust 61](#_Toc485987051)

[2012 Min 61](#_Toc485987052)

[The effects of disk and dust structure on observed polarimetric images of protoplanetary disks 62](#_Toc485987053)

[modelling (understand effects of dust particle structure/size-dependent grain settling/instrumental properties), different dust particle models and disk structures, particle size and shape have strong effect on brightness/detectability of disk, realistic models give very different results than homogeneous sphere model, need to also simulate telescope effects before interpretation of results 62](#_Toc485987054)

[2012 Weidling 62](#_Toc485987055)

[Free collisions in a microgravity many-particle experiment. 62](#_Toc485987056)

[I. Dust aggregate sticking at low velocities 62](#_Toc485987057)

[sticking threshold velocity of mm dust aggregates could not be reached in the lab so far -> microgravity experiments (> 0.1 cm/s, 0.5 – 2 mm), sticking for few collisions (0.2 – 3 cm/s) -> no sharp bouncing barrier, dust collision model -> deduced velocity below dust will always stick (8 x 10-5 m/s for mm dust) 62](#_Toc485987058)

[2011 Geretshauser 63](#_Toc485987059)

[Collisions of inhomogeneous pre-planetesimals 63](#_Toc485987060)

[Modelling (preplanetesimals (inhomogeneous, fluffy, porous, dust aggregates), subsequent collisions), inhomogeneity model based on: density distribution of dust aggregates, typical size of aggregates (cm), smoothed particle hydrodynamics code, porosity model, results: inhomogeneous preplanetesimals more likely destroyed than homogeneous aggregates, size of fragments decreases with increasing inhomogeneity => possible obstacle to collisional growth (active history = weaker aggregate) 63](#_Toc485987061)

[2011 Teiser 64](#_Toc485987062)

[Impact angle influence in high velocity dust collisions during planetesimal formation 64](#_Toc485987063)

[dust aggregate(from m particles) collisions, small (1-5 mm) on target, 20 m/s, 0° - 45°, supports sweep-up planetesimal formation 64](#_Toc485987064)

[2011 Beitz 64](#_Toc485987065)

[LOW-VELOCITY COLLISIONS OF CENTIMETER-SIZED DUST AGGREGATES 64](#_Toc485987066)

[lab dust (cm – decimeter size) collisions, setup 1 - microgravity (8x10-3 – 2 m/s), setup 2 - mass transfer (fragmentation velocity 20 cm/s), critical energy for disruptive collisions Q\* two orders of magnitude lower than in literature, accretion efficiency (few %) depends on impact velocity & porosity 64](#_Toc485987067)

[2011 Schräpler 64](#_Toc485987068)

[The physics of protoplanetesimal dust agglomerates. 65](#_Toc485987069)

[VI. Erosion of large aggregates as a source of micrometer-sized particles 65](#_Toc485987070)

[Collision experiments (erosion of macroscopic dust agglomerates (μm-sized silica spheres) via impact of μm-sized particles), initial phase (impact erodes up to 10 particles), then compression by impacts (partial passivation of agglomerate) => no erosion for v <̰ 30 m/s, erosion reduced by 1 order of magnitude for v >̰ 30 m/s, confirmed by numerical model, built analytical disk model => erosion is strong source of μm-sized particles in pp disk, explains observations (Furlan et.al) 65](#_Toc485987071)

[2010 Blum 65](#_Toc485987072)

[Dust growth in protoplanetary disks – a comprehensive experimental/theoretical approach 65](#_Toc485987073)

[review (lab & modelling), collisional sticking alone not enough, streaming and gravitational instability best candidates for planetesimal growth in protoplanetary disk 65](#_Toc485987074)

[2010 Kothe 65](#_Toc485987075)

[The physics of protoplanetesimal dust agglomerates. 66](#_Toc485987076)

[V. Multiple impacts of dusty agglomerates at velocities above the fragmentation threshold 66](#_Toc485987077)

[Collision experiments on mass transfer in shattering collisions (lab + drop tower, agglomerates of μm-sized silica spheres as projectile + target (volume filling factors: 0.15 & 0.45 respectively), velocities 1.5 – 6 m/s), result: linear increase of accretion efficiency with impact v (12 – 21 % of projectile mass), growth of conical structure on target after < 100 impacts (volume filling factor: 0.15 – 0.4, increasing with increasing impact v) 66](#_Toc485987078)

[2010 Zsom 66](#_Toc485987079)

[The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals? 66](#_Toc485987080)

[II. Introducing the bouncing barrier 66](#_Toc485987081)

[collision model based on lab experiments (dust aggregates), investigation of upper size limits for coagulation in protoplanetary disks, dust is modelled as spheres with porous and compact phases (continuous transition), include Brownian motion/radial drift/turbulence, 1 AU, midplane, different gas densities, catastrophic fragmentation very rare, quasi-steady states in distribution function by bouncing, turbulence has non-linear influence, aerodynamic size sorting of particles 66](#_Toc485987082)

[2010 Güttler 67](#_Toc485987083)

[The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals? 67](#_Toc485987084)

[I. Mapping the zoo of laboratory collision experiments 67](#_Toc485987085)

[complete collision model for protoplanetary dust, based on old literature/new experiments/simple physical model, four different kinds of sticking/two kinds of bouncing/three kinds of fragmentation, similar-sized/different-sized bodies 67](#_Toc485987086)

[2009 Teiser 68](#_Toc485987087)

[Decimetre dust aggregates in protoplanetary discs 68](#_Toc485987088)

[collision experiments, SiO2 (m) aggregates (sub-mm) with dust targets, 7.7 m/s (expected for decimetre size bodies in protoplanetary disks), part of projectile sticks directly, small parts aggregate later by gravity, crust growing (several cm thick), initially very porous (31 % filing), compacting in consecutive collisions, average COR 0.29 68](#_Toc485987089)

[2009 Mutschke 68](#_Toc485987090)

[Laboratory-based grain-shape models for simulating dust infrared spectra 69](#_Toc485987091)

[Lab and calculated dust extinction spectra often not in good agreement, modelling with distribution of form factors (DFF) to match lab results -> later grain shapes can be derived from model fits independently 69](#_Toc485987092)

[2009 Weidling 69](#_Toc485987093)

[The physics of protoplanetesimal dust agglomerates 69](#_Toc485987094)

[III. Compaction in multiple collisions 69](#_Toc485987095)

[Collision experiments (highly porous (volume filling factor 0.15) dust aggregates (of spherical 1.5 μm grains) with solid plate, 0.2 m/s, multiple (≤ 2600) collisions with same aggregate), results: volume filling factor increased by a factor of > 2, fragmentation in few cases (not expected, as threshold is usually higher v) 69](#_Toc485987096)

[2009 Teiser 70](#_Toc485987097)

[High-velocity dust collisions: forming planetesimals in a fragmentation cascade with final accretion 70](#_Toc485987098)

[lab dust collisions, up to 56.5 m/s, cm – decimetre size targets, sub-mm – cm size projectiles, varying shape, projectiles > 1 mm -> slight erosion of target, decimetre targets don’t break up, small ejecta produced, projectiles < 1 mm accrete (even at high velocities 70](#_Toc485987099)

[2008 Wada 70](#_Toc485987100)

[NUMERICAL SIMULATION OF DUST AGGREGATE COLLISIONS. 70](#_Toc485987101)

[II. COMPRESSION AND DISRUPTION OF THREE-DIMENSIONAL AGGREGATES IN HEAD-ON COLLISIONS 70](#_Toc485987102)

[Numerical simulations (dust aggregate collisions, 3D head-on) 70](#_Toc485987103)

[2007 Wada 70](#_Toc485987104)

[NUMERICAL SIMULATION OF DUST AGGREGATE COLLISIONS. 71](#_Toc485987105)

[I. COMPRESSION AND DISRUPTION OF TWO-DIMENSIONAL AGGREGATES 71](#_Toc485987106)

[Numerical simulations (dust aggregate collisions, 2D head-on), compression & disruption, degree of maximum compression determined by ratio of rolling energy to breaking energy, ice aggregates become more compact than quartz aggregates (same impact conditions), aggregates harder to disrupt with increasing number of particles 71](#_Toc485987107)

[2007 Ormel 71](#_Toc485987108)

[Dust coagulation in protoplanetary disks: porosity matters 71](#_Toc485987109)

[Modelling (coupling between dust and gas depends on porosity, aim: quantify influence in turbulent disk, three regimes: hit-and-stick, compaction, fragmentation), results: three stages (initially growth driven by Brownian motion -> high porosity, then turbulent higher velocities -> compaction, then settling out to the mid-plane, aggregates can grow to (porous) sizes of ≈ 10 cm in a few thousand years, before raining out to mid-plane 71](#_Toc485987110)

[2006 Blum 72](#_Toc485987111)

[Dust agglomeration 72](#_Toc485987112)

[Review (physical interactions that lead to sticking in gaseous environments, morphologies of resulting dust aggregates, modelling (temporal evolution + mass distribution of aggregates)) 72](#_Toc485987113)

[2005 Wurm 72](#_Toc485987114)

[Growth of planetesimals by impacts at ~25 m/s 72](#_Toc485987115)

[dust (mm-size to cm-size target), v ≤ 25 m/s, net growth at high speed collisions, fast ejecta 500 m, 40 % of impact velocity) 72](#_Toc485987116)

[2004 Krause 73](#_Toc485987117)

[Growth and Form of Planetary Seedlings: Results from a Sounding Rocket Microgravity Aggregation Experiment 73](#_Toc485987118)

[Collision experiment (microgravity (sounding rocket), Brownian motion-induced collisions), results: dust agglomerates have fractal dimensions as low as 1.4, temporal evolution of mean agglomerate mass described by power law, collision cross section = geometrical cross section, mass-distribution function 73](#_Toc485987119)

[2004 Gail 73](#_Toc485987120)

[Radial mixing in protoplanetary accretion disks 73](#_Toc485987121)

[IV. Metamorphosis of the silicate dust complex 73](#_Toc485987122)

[Modelling (evolution of main dust components, chemical composition, Mg-Fe-silicates, Mg-silicates & Fe, advection-diffusion, radial mixing), resulting mineral mixtures are in rough agreement with matrix material of meteorites/cometary nuclei 73](#_Toc485987123)

[2002 Blum 73](#_Toc485987124)

[First results from the cosmic dust aggregation experiment codag 74](#_Toc485987125)

[Collision experiments (microgravity (sounding rocket, duration: several minutes), Brownian motion-induced coagulation process of μm-sized dust), result: subsequent collisions form fractal dust aggregates 74](#_Toc485987126)

[2000 Poppe 74](#_Toc485987127)

[Experiments on collisional grain charging of micron-sized preplanetary dust 74](#_Toc485987128)

[Collision experiments on collisional charging (μm-sized grains impacting target surface (non-conducting)), reason: former experiments (particles returning to target after rebound, particle deposition on targets in presence of conducting materials), results: collisional charging stronger than anticipated, needs to be considered (preplanetary dust aggregation, lightning formation in solar nebula, charged grain coupling to magnetic fields) 74](#_Toc485987129)

[2000 Poppe 74](#_Toc485987130)

[ANALOGOUS EXPERIMENTS ON THE STICKINESS OF MICRON-SIZED PREPLANETARY DUST 74](#_Toc485987131)

[different dust materials (silica, diamond, enstatite, silicon carbide), stickier than theoretically predicted, stickiness depends more on size/shape/roughness than on material 74](#_Toc485987132)

[2000 Blum 75](#_Toc485987133)

[Experiments on Sticking, Restructuring, and Fragmentation of Preplanetary Dust Aggregates 75](#_Toc485987134)

[Collision experiments (lab & microgravity (drop tower), small dust aggregates (of μm-sized particles) onto solid targets), results: slow impacts in lab: formation of fluffy dust layer (gravity induced compaction in that), fast impacts in microgravity (v > few m/s): disruption of agglomerates, slower impacts in microgravity: sticking and removal from target, slow impacts in microgravity: sticking probability = 1, formation of compact dust layer, slowest impacts in microgravity: no compaction -> growth of very porous dust layer. Computer simulations based on rolling friction force and break-up energy => planet formation: dust aggregates below a few cm in diameter not expected to be subject to impact compaction 75](#_Toc485987135)

[1999 Heim 75](#_Toc485987136)

[Adhesion and Friction Forces between Spherical Micrometer-Sized Particles 76](#_Toc485987137)

[Characterization experiments (adhesion, rolling friction force, silica microspheres, 0.5 – 2.5 μm), result: rolling friction force ≈ 100 x lower than adhesion 76](#_Toc485987138)

[1993 Blum 76](#_Toc485987139)

[Experimental Investigations on Aggregate-Aggregate Collisions in the Early Solar Nebula 76](#_Toc485987140)

[Collision experiments (vacuum, 2 mm-sized dust aggregates (ZrSiO4 ≤ 1 μm, 74 % porosity / SiO2 ≈ 12 nm, 97 % porosity), 0.15 – 4 m/s, central to grazing collisions, mass ratios of collision partners 1:1 & 1:66), results: no coagulation (sticking), low v: bouncing, high v: transition to fragmentation (1:1 experiment: transition @ v ≈ 1m/s (ZrSiO4), @ ≈ 4 m/s (SiO2) / 1:66 experiment: transition unclear), fragmentation of 1:1 ZrSiO4: abundance of small fragments increases with increasing v and decreasing impact parameter, power law mass distribution of fragments -> fragmentation model (constant free surface energy per unit surface area of fragments, impact parameter-dependent efficiency for transition of kinetic collision energy into free surface energy of fragments) -> predicts complete disintegration of the ZrSiO4 aggregates for v ≥ 50 m/s, prediction based on van der Waals-bonded constituents: ≈ 3 m/s, typical velocities for the preplanetary nebula -> catastrophic fragmentations could be frequent if aggregates formed by weak surface forces. 76](#_Toc485987141)

[1987 Kendall 77](#_Toc485987142)

[A new method for measuring the surface energy of solids 77](#_Toc485987143)

[Experiments (surface energy of Titania/Silica), measure elastic modulus of sub-μm powder assemblies 77](#_Toc485987144)

[1983 Kawakami 77](#_Toc485987145)

[Impact experiments on ice 77](#_Toc485987146)

[Collision experiments (cratering and fragmentation of pure ice targets, cylindrical projectiles (aluminium, poly-carbonate, teflon, pyrophyllite), 110 – 680 m/s), results: craters in ice about 2 times larger than in basalt in the same energy range, depth/diameter ratios (0.1 – 0.3) close to basalt values, specific energy for complete destruction of ice: ≈ 50 J/kg (two orders of magnitude lower than for basalt), very large impact craters (Callisto/Mimas) must have fractured the whole satellite 77](#_Toc485987147)

[1983 Haff 77](#_Toc485987148)

[Grain flow as a fluid-mechanical phenomenon 77](#_Toc485987149)

[model to describe flow of sand grains between plates 77](#_Toc485987150)

[1980 Weidenschilling 78](#_Toc485987151)

[Dust to Planetesimals: Settling and Coagulation in the Solar Nebula 78](#_Toc485987152)

[numerical model for computing simultaneous coagulation and settling (gravitational instability/non-Keplerian rotation of nebula), composite process forms km sized planetesimals 78](#_Toc485987153)

[1977 Weidenschilling 79](#_Toc485987154)

[Aerodynamics of solid bodies in the solar nebula 79](#_Toc485987155)

[drag force in solar nebula, collisions, size fractionation of bodies, velocities up to 104 cm/s (m sized objects) 79](#_Toc485987156)

[Dust + Chondrules 80](#_Toc485987157)

[2012 Beitz 80](#_Toc485987158)

[Free collisions in a microgravity many-particle experiment 80](#_Toc485987159)

[II: The collision dynamics of dust-coated chondrules 80](#_Toc485987160)

[microgravity collisions of dust, chondrules, chondrules with dust, dust coated chondrules (2 – 3 mm, 0.18 – 0.58 chondrule volume filling), few cm/s sticking velocity for dust coated chondrules, collisions with material mix (dust coated chondrule or chondrules colliding with dust) stickier than single materials, chondrules might act as catalyser for planetesimal growth 80](#_Toc485987161)

[Ice, Dust, C 81](#_Toc485987162)

[2002 Kouchi 81](#_Toc485987163)

[Rapid Growth of asteroids owing to very sticky interstellar organic grains 81](#_Toc485987164)

[Experiments (organic covered ice and silicate grains), sticking threshold velocity 5m/s 81](#_Toc485987165)

[1993 Chokshi 81](#_Toc485987166)

[Dust Coagulation 81](#_Toc485987167)

[silicate, icy, carbonaceous grains, numerical modelling, collision of two smooth/elastic/spherical grains, critical velocity (bouncing barrier) grain size dependent, coagulation too slow for efficient growth, but efficiently removes small grains from cloud 81](#_Toc485987168)

[Ice + CO2 82](#_Toc485987169)

[2016 Musiolik 82](#_Toc485987170)

[Ice grain collisions in comparison: CO2, H2O, and their mixtures 82](#_Toc485987171)

[Collision experiments (CO2, H2O, 50 % mixture of both, 80 K, 1 mbar, 90 μm particle size), results: CO2 less sticky than H2O, more like silica, sticking threshold velocity increases with increasing water content 82](#_Toc485987172)

[2000 Arakawa 82](#_Toc485987173)

[Impact cratering of granular mixture targets made of H2O ice – CO2 ice – pyrophylite 82](#_Toc485987174)

[Collision experiments (3-component targets to simulate cometary nucleus/planetary regolith (H2O:CO2: pyrophylite = 1:1:0.74), nonheated/heated by thermal radiation), samples formed layer structure inside, results: cratering pattern strongly depends on sample history, nonheated targets: crates with regular shape, ejected volume ~ impact energy E, depth ~E0.5, thermally stratified samples: large amount of loose sub-crustal material ejected (sometimes leading to small hole and huge cavity underneath (velocity dependent). 82](#_Toc485987175)

[CO2 83](#_Toc485987176)

[2016 Musiolik 83](#_Toc485987177)

[COLLISIONS OF CO2 ICE GRAINS IN PLANET FORMATION 83](#_Toc485987178)

[lab experiments CO2 (snowline ≈ 10 AU), 80 K, particles (≈ 100 m and target, 0 – 2.5 m/s, bouncing barrier ≈ 0.04 m/s, fragmentation > 1 m/s, analytical model for COR and fragmentation strength, collisional behaviour resembles dust, one order of magnitude smaller bouncing barrier, collisional growth most likely between H2O and CO2 snowlines 83](#_Toc485987179)

[CO 84](#_Toc485987180)

[2013 Qi 84](#_Toc485987181)

[Imaging of the CO snow line in a solar nebula analog 84](#_Toc485987182)

[chemical imaging of CO snowline (TW Hya, solar nebula analogue) with ALMA, observe N2H+, distribution in ring matches predicted position (30 AU) of CO snow line, helps to assess models of solar system 84](#_Toc485987183)

[C/O Ratio 85](#_Toc485987184)

[2011 Öberg 85](#_Toc485987185)

[THE EFFECTS OF SNOWLINES ON C/O IN PLANETARY ATMOSPHERES 85](#_Toc485987186)

[C/O ratio regulates chemistry in hot Jupiters, exoplanets show different C/O ratio from solar system, ratio depends on where w.r.t. the different snow lines the giant planets form, between H2O and CO snowline, most of O is present in icy grains 85](#_Toc485987187)

[Surface Chemistry 86](#_Toc485987188)

[2002 Fraser 86](#_Toc485987189)

[Laboratory surface astrophysics experiment 86](#_Toc485987190)

[experiment designed to study surface ice chemistry in the lab (solid-gas interactions), 7 – 500 K, pressures 103 larger than in protoplanetary disks, gas composition H2 & CO, mass-spec/RAIRS/quartz crystal microbalance all in one chamber 86](#_Toc485987191)

[ISM Molecules 87](#_Toc485987192)

[2011 van Dishoeck 87](#_Toc485987193)

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[observations (80 sources), molecules: H2O/H218O/CO/13CO/C18O/OH+/H2O+/dust continuum, lack of water in cold gas, strong water emission from shocks, UV radiational heating of gas in outflow, H2O generally not the dominant coolant in warm dense gas around protostars 87](#_Toc485987196)

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[2007 Desch 89](#_Toc485987205)

[Mass distribution and planet formation in the Solar Nebula 89](#_Toc485987206)

[Disk model for Solar System, assume compact disk that is photoevaporated, solves problem that “minimum-mass” (assuming that giant planets swept up all material in their feeding zones) disk models have: Uranus and Neptune could not have grown to current size within lifetime of disk. This models derives planet masses within 10 % of actual masses, but only if Uranus and Neptune switched placed in early Solar System (also predicted by Nice model). 89](#_Toc485987207)

[1997 Chiang 89](#_Toc485987208)

[Spectral energy distributions of T Tauri stars with passive circumstellar disks 90](#_Toc485987209)

[Hydrostatic, radiative equilibrium disk models, disks encased by thin layer of superheated dust grains, result: disks flare & absorb more stellar radiation than flat disks would, spectral features from dust grains in superheated layer appear in emission if disk is viewed nearly face-on 90](#_Toc485987210)

[1997 Bell 90](#_Toc485987211)

[The structure and appearance of protostellar accretion disks: limits on disk flaring 90](#_Toc485987212)

[Vertical structure models of protostellar α-law accretion disks: temperature dependence of opacity is crucial factor determining radial trends, most planet formation (0.5 – 3 M1 disks) occurred in environments unheated by stellar radiation, external heating enhances flaring, but inner disk will shield planet-forming regions in most cases 90](#_Toc485987213)

[Other Materials 91](#_Toc485987214)

[2013 Krijt 91](#_Toc485987215)

[Energy dissipation in head-on collisions of spheres 91](#_Toc485987216)

[Modelling COR (treat adhesion + viscoelasticity self-consistently, add up energy losses from deformation), viscoelasticity can increase enery dissipation (increasing sticking velocity), collisions above sticking velocity remain dissipative, comparison with lab experiments, model reproduced ε(v) relation observed in experiments (wide range of materials + particle sizes), adhesion + viscoelasticity + deformation are required for realistic model 91](#_Toc485987217)

[2013 Güttler 91](#_Toc485987218)

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[Summary of experimental data (COR for various materials), preparation for model paper, digitized data of all summarised experiments provided with the article 91](#_Toc485987220)

[2009 Grasselli 92](#_Toc485987221)

[Velocity-dependent restitution coefficient and granular cooling in microgravity 92](#_Toc485987222)

[Microgravity experiments on granular cooling (vibrated granular medium, inelastic iron beads, 2D geometry, high-speed camera), results: COR (low v: ε increasing with v), time decay of energy in the system (cooling time much shorter than could be explained by constant or decreasing ε), better agreement between experiment and theory requires taking into account either rotational degree of freedom or v-dependence of ε. 92](#_Toc485987223)

[2009 Sorace 92](#_Toc485987224)

[High apparent adhesion energy in the breakdown of normal restitution for binary impacts of small spheres at low speed 92](#_Toc485987225)

[Collision experiments (head-on, two identical small particles, acrylic/ceramic/steel, suspended by resilient strands, impact velocity low enough for adhesion), COR lowered by adhesion, apparent adhesion surface energy larger than expected 92](#_Toc485987226)

[2006 Reissaus 92](#_Toc485987227)

[Sticking efficiency of nanoparticles in high-velocity collisions with various target materials 92](#_Toc485987228)

[Collision experiments (Al2O3 (5 – 50 nm) & C (10 – 20 nm) particles produced by laser ablation, impacting on target (C, Au, grease), 10-5 mbar, 1 km/s, sticking efficiency measured by microbalance), result: moderate to high sticking probabilities -> capture and retrieval of atmospheric particles feasible 92](#_Toc485987229)

[1994 Nuth 93](#_Toc485987230)

[Magnetically Enhanced Coagulation of Very Small Iron Grains 93](#_Toc485987231)

[Experiments (high coagulation efficiency of 20 nm-sized iron grains, produced in low-pressure H-atmosphere in magnetic field (100 Gauss) -> permanently magnetized), such grains could have been produced in solar nebula by procession of interstellar grains -> could act as “net” for sweeping up silicates -> aid planetesimal formation 93](#_Toc485987232)

[1993 Love 93](#_Toc485987233)

[Target Porosity Effects in Impact Cratering and Collisional Disruption 93](#_Toc485987234)

[Collision experiments ((soda lime glass projectiles, porous sintered glass targets, hypervelocity), results: Increased target porosity leads to deeper crater penetration, lower spall velocities, and greater localization of the impact damage, specific energy threshold for target destruction ~ (1-porosity)-3.6, experiments also produced melt-lined agglutinate crater pits 93](#_Toc485987235)

[1984 Takagi 93](#_Toc485987236)

[Impact Fragmentation Experiments of Basalts and Pyrophyllites 94](#_Toc485987237)

[Collision experiments (basalt/pyrophyllite targets (20 g – 3.3 kg), aluminum projectiles (2 – 20 g), 70 – 990 m/s), results: size distribution of fragments (power-law) dependent on nondimensional impact stress (PI = P0/Y · (L/R)3, P0 = peak shock pressure, Y = material strength of target, L = projectile size, R = target size) and on material (larger fragments for aluminum target than for brittle target at same PI) 94](#_Toc485987238)

# H2O Vapour

## 2013 Podio

### WATER VAPOR IN THE PROTOPLANETARY DISK OF DG Tau

#### water vapour detected in outer disk, where most water ice reservoirs are stored, Herschel observations, dominated by emission from envelope/outflow, strong UV radiation of parent star irradiates upper disk layer (heating to ≈ 600 K), suggest water delivery to terrestrial planets by impact of icy bodies forming in outer disk

Water is key in the evolution of protoplanetary disks and the formation of comets and icy/water planets. While high-excitation water lines originating in the hot inner disk have been detected in several T Tauri stars (TTSs), water vapor from the outer disk, where most water ice reservoirs are stored, was only reported in the nearby TTS TW Hya. We present spectrally resolved *Herschel*/HIFI observations of the young TTS DG Tau in the ortho- and para-water ground-state transitions at 557 and 1113 GHz. The lines show a narrow double-peaked profile, consistent with an origin in the outer disk, and are ∼19–26 times brighter than in TW Hya. In contrast, CO and [C ii] lines are dominated by emission from the envelope/outflow, which makes H2O lines a unique tracer of the disk of DG Tau. Disk modeling with the thermo-chemical code ProDiMo indicates that the strong UV field, due to the young age and strong accretion of DG Tau, irradiates a disk upper layer at 10–90 AU from the star, heating it up to temperatures of 600 K and producing the observed bright water lines. The models suggest a disk mass of 0.015–0.1 M⊙, consistent with the estimated minimum mass of the solar nebula before planet formation, and a water reservoir of ∼102–103 Earth oceans in vapor and ∼100 times larger in the form of ice. Hence, this detection supports the scenario of ocean delivery on terrestrial planets by the impact of icy bodies forming in the outer disk.

# Ice

## 2016 Deckers

18 January , Teiser

### Collisions of solid ice in planetesimal formation

#### collision experiments (water ice), cm projectiles on decimetre targets, 15 – 45 m/s, 255.8 K, disruptive sticking (low efficiency), upper threshold depends on projectile size (no mass transfer above that), near snowline evaporation and condensation expected to produce solid ice, free fall collisions (7 m/s, cm ice spheres, fragmentation threshold & COR)

We present collision experiments of centimetre projectiles on to decimetre targets, both made up of solid ice, at velocities of 15 m/s to 45 m/s at an average temperature of Tavg = 255.8 ± 0.7 K. In these collisions the centimetre body gets disrupted and part of it sticks to the target. This behaviour can be observed up to an upper threshold, that depends on the projectile size, beyond which there is no mass transfer. In collisions of small particles, as produced by the disruption of the centimetre projectiles, we also find mass transfer to the target. In this way the larger body can gain mass, although the efficiency of the initial mass transfer is rather low. These collision results can be applied to planetesimal formation near the snowline, where evaporation and condensation is expected to produce solid ice. In free fall collisions at velocities up to about 7 m/s, we investigated the threshold to fragmentation and coefficient of restitution of centimetre ice spheres.

## 2016 Jost

15 September 2015 , Pommerol, Poch, Gundlach, Leboeuf, Dadras, Blum, Thomas

### Experimental characterization of the opposition surge in fine-grained water–ice and high albedo ice analogs

#### Characterisation experiments (bidirectional reflectance, VIS-NIR, surfaces built from small-grained spherical water-ice particles), results: coherent backscattering dominates for fresh samples, contribution decreases with increasing bulk porosity and particle shape irregularity, particle sintering (temporal effect), glory for granular surfaces formed by small particles, angular positon of glory depends on particle size

We measured the bidirectional reflectance in the VIS–NIR spectral range of different surfaces prepared from small-grained spherical water–ice particles over a wide range of incidence and emission geometries, including opposition. We show that coherent backscattering is dominating the opposition effect on fresh sample material, but its contribution decreases when particles become more irregularly shaped and the bulk porosity increases. Strong temporal evolution of the photometric properties of icy samples, caused by particle sintering and resulting in a decrease of backscattering, is shown. The sintering of the ice particles is documented using cryo-SEM micrographs of fresh and evolved samples. To complement the photometric characterization of ices, multiple high albedo laboratory analogs were investigated to study the effects of shape, grain size distribution, wavelength and surface roughness. In addition to the main backscattering peak, the phase curves also display the effect of glory in the case of surfaces of granular surfaces formed by either spherical ice or glass particles. We show that the angular position of the glory can be used to determine accurately the average size of the particles. Reflectance data are fitted by the Hapke photometric model, the Minnaert model and three morphological models. The resulting parameters can be used to reproduce our data and compare them to the results of other laboratory experiments and astronomical observations.

## 2015 Fukazawa

13 October , Arakawa, Yamauchi, Sekine, Kobyashi, Uwatoko, Chi, Fernendez-Baca

### Properties of Ferroelectric Ice

#### Characterisation (neutron diffraction, D2O with impurities (KOD, NaOD, LiOD, DCl, ND3, Ca(OD)2), atmospheric pressure) of “ferroelectric ice” (= ice XI, can generate giant electric fields), stable @ 57 – 74 K, can be important for planet formation, results: ferroelectric ice forms with dopants that produce L-defects (KOD, NaOD), no ferroelectricity observed for samples with D-defect

Various forms of ice exist within our galaxy, from interstellar clouds to comets, moons and planets. Particularly intriguing type of ice - “ferroelectric ice”, which can sustain a giant electric field was discovered experimentally and is stable in the temperature range 57-74 K. This form of ice, named ice XI, can generate enormous electric fields and can play an important role in planetary formation. We measured neutron diffraction profiles of D2O ice with impurities to investigate the formation of ice XI under atmospheric pressure. We made powder samples of ice doped with KOD, NaOD, LiOD, DCl, ND3 and Ca(OD)2. We carried out Rietveld analysis for diffraction profiles and obtained the mass fraction f (the ratio of the mass of ice XI to that of the doped ice). A significant amount of ferroelectric ice is observed in ice samples with dopants, which produce L-defect. The values of f of ice doped with 0.01 – 0.001-M KOD or NaOD is generally higher than those with 0.1-M KOD or NaOD. On the other hand, ice samples with D-defect, did not become ferroelectric ice. On the basis of the neutron diffraction data we have discussed the properties of ferroelectric ice.

## 2015 Gundlach

19 October 2014 , Blum

### The stickiness of micrometer-sized water-ice particles

#### Collision experiments (μm-sized ice particles growing aggregates, 114 – 260 K), results: threshold velocity for sticking: 9.6 m/s below 210 K, increasing with T above 210 K, threshold velocity ≈ 10 x larger than for μm-sized silica particles, erosion of aggregates: v > 15.3 m/s, specific surface energy, viscous relaxation time

Water ice is one of the most abundant materials in dense molecular clouds and in the outer reaches of protoplanetary disks. In contrast to other materials (e.g., silicates), water ice is assumed to be stickier due to its higher specific surface energy, leading to faster or more efficient growth in mutual collisions. However, experiments investigating the stickiness of water ice have been scarce, particularly in the astrophysically relevant micrometer-sized region and at low temperatures. In this work, we present an experimental setup to grow aggregates composed of μm-sized water-ice particles, which we used to measure the sticking and erosion thresholds of the ice particles at different temperatures between 114 K and 260 K. We show with our experiments that for low temperatures (below ~210 K), μm-sized water-ice particles stick below a threshold velocity of 9.6 m s–1, which is approximately 10 times higher than the sticking threshold of μm-sized silica particles. Furthermore, erosion of the grown ice aggregates is observed for velocities above 15.3 m s–1. A comparison of the experimentally derived sticking threshold with model predictions is performed to determine important material properties of water ice, i.e., the specific surface energy and the viscous relaxation time. Our experimental results indicate that the presence of water ice in the outer reaches of protoplanetary disks can enhance the growth of planetesimals by direct sticking of particles.

## 2015 Hill

23 December 2014 , Heißelmann, Blum, Fraser

### Collisions of small ice particles under microgravity conditions

### II. Does the chemical composition of the ice change the collisional properties?

#### Collision experiments (1.5 cm ice spheres (pure / 5 % methanol / 5 % formic acid), 0.01 – 0.19 m/s, 131 – 160 K, 10-5 mbar), results: range of COR values, no correlation to chemical composition / velocity / temperature, surface roughness is dominant factor in explaining range of COR

*Context.* Understanding the collisional properties of ice is important for understanding both the early stages of planet formation and the evolution of planetary ring systems. Simple chemicals such as methanol and formic acid are known to be present in cold protostellar regions alongside the dominant water ice; they are also likely to be incorporated into planets which form in protoplanetary disks, and planetary ring systems. However, the effect of the chemical composition of the ice on its collisional properties has not yet been studied.

*Aims.* Collisions of 1.5 cm ice spheres composed of pure crystalline water ice, water with 5% methanol, and water with 5% formic acid were investigated to determine the effect of the ice composition on the collisional outcomes.

*Methods.* The collisions were conducted in a dedicated experimental instrument, operated under microgravity conditions, at relative particle impact velocities between 0.01 and 0.19 ms-1, temperatures between 131 and 160 K and a pressure of around 10-5 mbar.

*Results.* A range of coefficients of restitution were found, with no correlation between this and the chemical composition, relative impact velocity, or temperature.

*Conclusions.* We conclude that the chemical composition of the ice (at the level of 95% water ice and 5% methanol or formic acid) does not affect the collisional properties at these temperatures and pressures due to the inability of surface wetting to take place. At a level of 5% methanol or formic acid, the structure is likely to be dominated by crystalline water ice, leading to no change in collisional properties. The surface roughness of the particles is the dominant factor in explaining the range of coefficients of restitution.

## 2014 Hill

8 October , Heißelmann, Blum, Fraser

### Collisions of small ice particles under microgravity conditions

#### Collision experiments (microgravity, icy particles (4.7 – 10.8 mm diameter, spherical or irregular fragments), 0.27 – 0.51 m/s, 131 – 160 K) colliding with each other, impact parameters: 0 - 1), results: mostly bouncing, few cases of fragmentation, COR evenly spread between 0.08 – 0.65 (average 0.36), ≥ 58 % translational energy lost, ≤ 17 % translational converted to rotational energy, COR not affected by temperature

*Context*. Planetesimals are thought to be formed from the solid material of a protoplanetary disk by a process of dust aggregation. It is not known how growth proceeds to kilometre sizes but it has been proposed that water ice beyond the snow line might impact this process.

*Aims*. In order to better understand collisional processes in protoplanetary disks leading to planet formation, individual low velocity collisions of small ice particles were investigated.

*Methods*. The particles were collided together under microgravity conditions on a parabolic flight campaign using a purpose built, cryogenically cooled experimental setup. The setup was capable of colliding together pairs of small ice particles (between 4.7 and 10.8 mm in diameter) at relative collision velocities of between 0.27 and 0.51 m/s at temperatures between 131 and 160 K. Two types of ice particle were used; ice spheres and irregularly shaped ice fragments.

*Results*. Bouncing was observed in the majority of cases with a few cases of fragmentation. A full range of normalised impact parameters (b/R = 0.0-1.0) was realised with this apparatus. Coefficients of restitution were evenly spread between 0.08 and 0.65 with an average value of 0.36, leading to a minimum of 58% of translational energy being lost in the collision. Analysis of particle rotation showed that up to 17% of the energy of the particles before the collision was converted into rotational energy. Temperature did not impact coefficients of restitution over the range studied.

## 2014 Yasui

4 February , Hayama, Arakawa

### Impact strength of small icy bodies that experienced multiple collisions

#### Collision experiments (multiple impacts, polycrystalline target, cylindrical projectile, 258 – 263 K, 84 – 502 m/s), results: impact strength: 77.6 J/kg, number of fine fragments depends on energy density at collision -> crater size distribution of Phoebe (Saturnian icy satellite), impact velocity dependence

Frequent collisions are common for small bodies in the Solar System, and the cumulative damage to these bodies is thought to significantly affect their evolution. It is important to study the effects of multiple impacts such as the number of impacts on the impact strength and the ejection velocity of impact fragments. Here we conducted multiple-impact experiments using a polycrystalline water ice target, varying the number of impacts from 1 to 10 times. An ice cylindrical projectile was impacted at 84–502 m/s by using a single-stage gas gun in a cold room between -10 and -15 °C. The impact strength of the ice target that experienced a single impact and multiple impacts is expressed by the total energy density applied to the same target, ΣQ, and this value was observed to be 77.6 J/kg. The number of fine impact fragments at a fragment mass normalized by an initial target mass, m/Mt0 ≈ 10-6, nm, had a good correlation with the single energy density at each shot, Qj, and the relationship was shown to be nm = 101.02 ± 0.22 · Qj1.31 ± 0.12. We also estimated the cumulative damage of icy bodies as a total energy density accumulated by past impacts, according to the crater scaling laws proposed by Housen et al. (Housen, K.R., Schmidt, R.M., Holsapple, K.A. [1983]. J. Geophys. Res. 88, 2485–2499) of ice and the crater size distributions observed on Phoebe, a saturnian icy satellite. We found that the cumulative damage of Phoebe depended significantly on the impact speed of the impactor that formed the craters on Phoebe; and the cumulative damage was about one-third of the impact strength ΣQ\* at 500 m/s whereas it was almost zero at 3.2 km/s.

## 2014 Aumatell

7 October 2013 , Wurm

### Ice aggregate contacts at the nm-scale

#### Experiments (nm ice particles), thermal gradient force microscope (measure pull-off forces/twisting torques), ice aggregates in astrophysical settings more robust against restructuring than originally thought, likely grow as fractal aggregates to larger size before they restructure, retain high porosity

Aggregation of ice particles is a fundamental process in the interstellar medium as well as in planet formation. Dedicated to study the contact physics of nm-ice particles, we developed a thermal gradient force microscope. This allows us and was used to measure pull-off forces with a resolution on the nN-scale and to measure rolling. Furthermore, based on a free probe, it also allows us to study twisting torques for the first time. The experiments show that torques required to twist are significantly larger than that macroscopic models scaled down to the nm-size range would predict. This implies that (ice) aggregates in astrophysical settings with small constituents are more robust against restructuring than previously thought. They likely grow as fractal aggregates to larger size before they restructure, and during later compact growth they likely retain a higher porosity during further evolution towards planetesimals.

## 2012 Shimaki

3 August , Arakawa

### Low-velocity collisions between centimeter-sized snowballs: Porosity dependence of coefficient of restitution for ice aggregates analogues in the Solar System

#### Collision experiments (free-fall, cm-size, sintered snowballs, 44 – 80 % porosity, impact velocity: 0.44 – 4.12 m/s, 263 K), sticking dominant for porosity > 70 %, else bouncing dominant, COR depends strongly on porosity rather than velocity, decrease with increasing porosity, dynamic compressive strength of snow measure from impact compaction (consistent with upper limit of static compressive strength, analysis of collisions using Johnson’s model

Understanding the collisional behavior of ice dust aggregates at low velocity is a key to determining the formation process of small icy bodies such as icy planetesimals, comets and icy satellites, and this collisional behavior is also closely related to the energy dissipation mechanism in Saturn’s rings. We performed head-on collision experiments in air by means of free-falling centimeter-sized sintered snowballs with porosities from 44% to 80% at impact velocities from 0.44 m/s to 4.12 m/s at -10 °C. In cases of porosity larger than 70%, impact sticking was the dominant collision outcome, while bouncing was dominant at lower porosity. Coefficients of restitution of snow in this velocity range were found to depend strongly on the porosity rather than the impact velocity and to decrease with the increase of the porosity. We successfully measured the compaction volume of snowballs after the impact, and it enabled us to estimate the dynamic compressive strength of snow with the assumption of the energy conservation between kinetic energy and work for deformation, which was found to be consistent with the upper limit of static compressive strength. The velocity dependence of coefficients of restitution of snow was analyzed using a Johnson’s model, and a diagram for collision outcomes among equal-sized sintered snowballs was successfully drawn as a function of porosity and impact velocity.

## 2012 Shimaki

27 January , Arakawa

### Experimental study on collisional disruption of highly porous icy bodies

#### Collision experiments (sintered porous ice spheres on targets, porosity 40 – 70 %, 2.4 – 489 m/s), results: sticking above threshold velocity (porosity dependent: decreasing with increasing velocity, 44 m/s @ 60 %, 13 m/s @ 70 %), shattering strength of target decreases with increasing porosity (100 j/kg @ 40 %, 31 J/kg @ 70 %), antipodal velocity increased with increasing energy density and porosity, fragment mass distribution depends on porosity and energy density

Knowing the collisional process among small porous icy bodies in the outer solar system is a key to understanding the formation of EKBOs and the evolution of icy planetesimals. Impact experiments of sintered porous ice spheres with 40%, 50%, 60% and 70% porosity were conducted by using three types of projectiles at the impact velocity from 2.4 to 489 m/s, and we studied the effects of porosity on the collisional processes. Projectile sticking occurred at the impact velocity higher than 44 m/s for 60% porosity targets and higher than 13 m/s for 70% porosity targets. The antipodal velocity of the porous ice target increased with the increase of energy density, Q, and it increased slightly with the increase of porosity, although it was exceptionally high in cases when the projectile penetrated the target. The shattering strength of porous ice targets was found to decrease from 100 to 31 J/kg with the increase of porosity from 40% to 70%. The cumulative fragment mass distribution was found to depend on the energy density and the target porosity, and the slopes of the distribution in the small fragment region were almost flat for more porous targets. We reanalyzed the cumulative fragment mass distribution and first obtained the empirical equation showing the fragment mass distribution of porous ice targets as a function of the energy density and the porosity.

## 2010 Schegerer

29 April , Wolf

### Spatially resolved detection of crystallized water ice in a T Tauri object

#### spectroscopic detection of crystalline water ice in young stellar object, predominantly small grains (0.1 – 0.3 μm), few large grains, evidence for grain growth, crystallinity increases in upper layers of circumstellar disk, only amorphous grains exist in bipolar envelope, crystallization close to disk atmosphere, where water ice is shielded from hard radiation

*Aims.* We search for frozen water and its processing around young stellar objects (YSOs of class I/II). We try to detect potential, regional differences in water ice evolution within YSOs, which is relevant to understanding the chemical structure of the progenitors of protoplanetary systems and the evolution of solid materials. Water plays an important role as a reaction bed for rich chemistry and is an indispensable requirement for life as known on Earth.

*Methods.* We present our analysis of NAOS-CONICA/VLT spectroscopy of water ice at 3 μm for the T Tauri star YLW 16 A in the ρ Ophiuchi molecular cloud. We obtained spectra for different regions of the circumstellar environment. The observed absorption profiles are deconvolved with the mass extinction profiles of amorphous and crystallized ice measured in laboratory. We take into account both absorption and scattering by ice grains.

*Results.* Water ice in YLW16A is detected with optical depths of between τ = 1.8 and τ = 2.5. The profiles that are measured can be fitted predominantly by the extinction profiles of small grains (0.1 μm – 0.3 μm) with a small contribution from large grains (< 10 %). However, an unambiguous trace of grain growth cannot be found. We detected crystallized water ice spectra that have their origin in different regions of the circumstellar environment of the T Tauri star YLW 16 A. The crystallinity increases in the upper layers of the circumstellar disk, while only amorphous grains exist in the bipolar envelope. As in studies of silicate grains in T Tauri objects, the higher crystallinity in the upper layers of the outer disk regions implies that water ice crystallizes and remains crystallized close to the disk atmosphere where water ice is shielded against hard irradiation.

## 2010 Heißelmann

18 August 2009 , Blum, Fraser, Wolling

### Microgravity experiments on the collisional behavior of saturnian ring particles

#### Collision experiments (microgravity), I. parabolic flight (1.5 cm spheres, 6 – 22 cm/s, cryogenic temperatures), results: uniform distribution of COR between 0.06 – 0.84 (0.45 mean), II. mini lab drop tower (ensemble of cm-sized glass beads), results: kinetic energy development of system can be described by granular fluid model (Haff’s law) with a constant COR of 0.64, setup suitable for velocities ≤ 5 mm/s

In this paper we present results of two novel experimental methods to investigate the collisional behavior of individual macroscopic icy bodies. The experiments reported here were conducted in the microgravity environments of parabolic flights and the Bremen drop tower facility. Using a cryogenic parabolic-flight setup, we were able to capture 41 near-central collisions of 1.5-cm-sized ice spheres at relative velocities between 6 and 22 cm/s. The analysis of the image sequences provides a uniform distribution of coefficients of restitution with a mean value of ε̅ = 0.45 and values ranging from ε = 0.06 to 0.84. Additionally, we designed a prototype drop-tower experiment for collisions within an ensemble of up to one hundred cm-sized projectiles and performed the first experiments with solid glass beads. We were able to statistically analyze the development of the kinetic energy of the entire system, which can be well explained by assuming a granular ‘fluid’ following Haff’s law with a constant coefficient of restitution of ε = 0.64. We could also show that the setup is suitable for studying collisions at velocities of < 5 mm/s appropriate for collisions between particles in Saturn’s dense main rings.

## 2010 Zamankhan

30 June 2009

### Simulations of collision of ice particles

#### develop realistic model for ice-structure interaction, analysis of Bridges 1984 ice ball experiments, difficult to predict onset of fragmentation/fracturing, most energy dissipation is result of racturing at contact surface, questions validity of constitutive models (e.g. Brilliantov/Hertzsch)

The objective of this paper is to develop a realistic model for ice–structure interaction. To this end, the experiments made by Bridges et al. [Bridges FG, Hatzes A, Liu DNC. Structure, stability and evolution of Saturn’s rings. Nature 1984;309:333–5] in order to measure the coefficient of restitution for ice particles are thoroughly analyzed. One particularly troublesome aspect of the aforementioned experiments is fracture of the ice particles during a collision. In the present effort, the collisional properties of the ice particles are investigated using a Finite Element approach. It is found that a major challenge in modeling collision of the ice balls is the prediction of the onset of fracture and crack propagation in them. In simulations of a block of ice collision to a structure, it is crucial that fracture is determined correctly, as it will influence the collisional properties of the ice particles. The results of the simulation, considering fracture criterion implemented into the Finite Element Model [Zamankhan P, Bordbar M-H. Complex flow dynamics in dense granular flows. Part I: experimentation. J Appl Mech (T-ASME) 2006;73:648–57; Zamankhan P, Huang J. Com- plex flow dynamics in dense granular flows. Part II: simulations. J Appl Mech (T-ASME) 2007;74:691–702] together with a material model for the ice, imply that most of the kinetic energy dissipation occurs as a result of fracturing at the contact surface of the ice particles. The results obtained in the present study suggest that constitutive models such as those proposed by Brilliantov et al. [Brilliantov NV, Spahn F, Hertzsch JM, Poschel T. Model for collisions in granular gases. Phys Rev E;1996;53:5382–92] for collisions of ice particles are highly questionable.

## 2007 Schäfer

4 Mai , Speith, Kley

### Collisions between equal-sized ice grain agglomerates

#### numerical study, collisional outcome of low velocity impacts, equal sized porous agglomerates (too large for lab experiments), growth for head-on collisions seems possible, but very little sticking for most material strengths, rotation for glancing collisions, no significant compaction for low velocity impacts

*Context.* Following the recent insight in the material structure of comets, protoplanetesimals are assumed to have low densities and to be highly porous agglomerates. It is still unclear if planetesimals can be formed from these objects by collisional growth.

*Aims.* Therefore, it is important to study numerically the collisional outcome from low velocity impacts of equal sized porous agglomerates which are too large to be examined in a laboratory experiment.

*Methods.* We use the Lagrangian particle method Smooth Particle Hydrodynamics to solve the equations that describe the dynamics of elastic and plastic bodies. Additionally, to account for the influence of porosity, we follow a previous developed equation of state and certain relations between the material strength and the relative density.

*Results.* Collisional growth seems possible for rather low collision velocities and particular material strengths. The remnants of collisions with impact parameters that are larger than 50% of the radius of the colliding objects tend to rotate. For small impact parameters, the colliding objects are effectively slowed down without a prominent compaction of the porous structure, which probably increases the possibility for growth. The protoplanetesimals, however, do not stick together for the most part of the employed material strengths.

*Conclusions.* An important issue in subsequent studies has to be the influence of rotation to collisional growth. Moreover, for realistic simulations of protoplanetesimals it is crucial to know the correct material parameters in more detail.

## 2005 Wang

, Bell, Iedema, Tsekouras, Cowin

### STICKY ICE GRAINS AID PLANET FORMATION: UNUSUAL PROPERTIES OF CRYOGENIC WATER ICE

#### Experiments, vapour deposited amorphous water ice (5 – 100 K), sticking, ≈ 10 % bouncing

There is limited time for the dust in the nebula around a newborn star to form planetesimals: in a few million years or less the star’s stellar winds will disperse most of the unagglomerated dust. It has been difficult to explain the efficiency by which dust grains must have agglomerated to form planetesimals in circumstellar disks. A major obstacle is the fragility of aggregates, leading to collisional fragmentation, which makes it difficult for them to grow to, and beyond, meter-sized bodies. The distinct properties of cryogenic (5–100 K) amorphous water ice, which composes or coats the grains in the cooler parts of the nebulae (≥ Jovian distances), may be able to account for the rapid agglomeration. Measurements are presented that show that this ice readily acquires persistent macroscopic electric dipoles, strongly enhancing grain-grain adhesion. In addition, measurements were made showing that vapor-deposited amorphous water ice is also highly mechanically inelastic (≈ 10% rebound). Together these may explain this efficient net sticking and net growth. Similar properties of higher temperature grains may aid agglomeration in the inner regions of the nebulae.

## 2004 Austen Angell

### AMORPHOUS WATER

#### ASW, characterization and production of different amorphous and glassy phases, glass transition, polyamorphicity

After providing some background material to establish the interest content of this subject, we summarize the many different ways in which water can be prepared in the amorphous state, making clear that there seems to be more than one distinct amorphous state to be considered. We then give some space to structural and spectroscopic characterization of the distinct states, recognizing that whereas there seems to be unambiguously two distinct states, there may be in fact be more, the additional states mimicking the structures of the higher-density crystalline polymorphs. The low-frequency vibrational properties of the amorphous solid states are then examined in some detail because of the gathering evidence that glassy water, while difficult to form directly from the liquid like other glasses, may have some unusual and almost ideal glassy features, manifested by unusually low states of disorder. This notion is pursued in the following section dealing with thermodynamic and relaxational properties, where the uniquely low excess entropy of the vitreous state of water is confirmed by three different estimates. The fact that the most nearly ideal glass known has no properly established glass transition temperature is highlighted, using known dielectric loss data for amorphous solid water (ASW) and relevant molecular glasses. Finally, the polyamorphism of glassy water, and the kinetic aspects of transformation from one form to the other, are reviewed.

## 2003 Flin

22 April , Brzoska, Lesaffre, Coléou, Pieritz

### Full three-dimensional modelling of curvature-dependent snow metamorphism: first results and comparison with experimental tomographic data

#### Numerical modelling (snow metamorphism, near 0°C), structure changes driven by temperature and humidity fields, high vapour pressure => metamorphism in first approximation curvature driven (neglecting crystallographic and diffusion-limited effects), basic equations: Kelvin & Langmuir-Knudsen, result: analytical growth law of ice phase

Snow, from its fall until its full melting, undergoes a structure metamorphism governed by temperature and humidity fields. Among the many possible mechanisms that contribute to snow metamorphism, those that depend only on curvature are the most accessible to modelling. The isothermal metamorphism of a dry snow sample near 0°C is addressed in this paper. Near 0°C, the vapour pressure of water is high: the metamorphism can be considered, in first approximation, as fully curvature-driven. This corresponds to neglect crystallographic orientation and diffusion-limited effects. Based on Kelvin’s and Langmuir–Knudsen equations, a growth law of the ice phase can be analytically obtained. In this law, the variation of the local volume fraction is proportional to the difference between integral and local curvatures. A simple numerical model was implemented in three dimensions and applied on real tomographic images.

## 2002 Hertzsch

31 May

### A model for surface effects in slow collisions of icy grains

#### numerical model, slow collisions, solid grains, planar motion, elasticity + viscosity + soft surface layers + adhesion + friction, COR components, water ice (cm size), critical velocity (bouncing sets in)

A model is presented which describes the change of the relative velocity of slowly colliding solid grains in planar motion. It takes into account elasticity and viscosity of the material, effects of soft surface layers and adhesion, and friction between the surfaces. The equations of motion of the colliding bodies are solved numerically. Normal and tangential restitution coefficients are computed, and their dependence on the components of the relative velocity before impact is determined. The material constants in the examples have been chosen to reflect the behaviour of water ice as an important material in the outer solar system. Soft surface layers as well as surface energy lead to aggregation for low collision velocities, both normal and tangential relative velocity can be reduced to zero at the same time. A critical velocity exists below which rebound is inhibited. It can be related to the thickness and properties of the surface layer or the surface energy of the collision partners. The results are expected to be important for the evolution of the size distribution in granular media, in particular for the formation of larger bodies from centimetre-sized grains.

## 1999 Arakawa

12 July

### Ejection velocities of ice fragments in oblique impacts of ice spheres

#### Collision experiments (-18°C, 170 – 640 m/s, ice spheres colliding), results: minimum ejection velocity decreases with increasing impact angle and increases with increasing specific energy (kinetic energy of projectile normalised to target mass), maximum ejecta velocity independent of impact angle and velocity, icy planets > 100 km radius can capture most fragments from collisions between 0 – 50°

Reaccumulation conditions of icy planetesimals in collisional disruption were studied experimentally using a one-stage light gas gun set in a cold room (−18°C). Oblique impacts between ice spheres were used to measure the velocity distributions of fragments. The impact velocities ranged from 170 to 640 m/s, and the projectile-to-target mass ratio was a constant and equal to 0.13. The collisional disruption was observed by ultra-high speed photography at a rate of 2×105 to 1×104 frames/s. As a result, we found that the minimum ejection velocity was related to the specific energy and the impact angle by: Vmin = 0.092Q′0.65, where Q′ ≡ Q(cosθ)5. Q is the specific energy defined as a ratio of projectile kinetic energy to target mass. On the other hand, high velocity ejecta caused by jetting was observed around the impact point, and the normalized maximum velocity was found to range from 1.6 to 3.1, irrespective of impact angle and impact velocity. The reaccumulation conditions were estimated in oblique impacts of 480 m/s with a mass ratio of 0.13 by comparing the ejecta velocity with the escape velocity of the icy planet. As a result, it was clarified that icy planets with radii larger than 100 km can capture most of the fragments in collisions with impact angles from 0 to 50°.

## 1999 Ryan

24 June , Davis, Giblin

### A Laboratory Impact Study of Simulated Edgeworth–Kuiper Belt Objects

#### Collision experiments (low-velocity airgun shots, target: porous/homogeneous ice spheres, projectile: aluminium/solid ice/fractured ice), results: porous targets as strong as solid targets (voids dissipate energy well), but aluminium projectile more damaging than solid ice, solid ice more damaging than fractured ice (lower penetration depth => less energy coupled into target), impact strength (porous targets impacted by porous/solid projectiles) > 5 x 105 erg/cm3

This paper reports on a series of laboratory impact experiments designed to provide basic data on how simulated Edgeworth–Kuiper belt objects (EKOs) fragment in an impact event. In September – October 1997 we carried out 20 low-velocity airgun shots at the Ames Vertical Gun Range into porous and homogeneous ice spheres using aluminum, fractured ice, and solid ice projectiles. We found that the porous ice targets behaved as strongly as solid ice in collision. Energy is apparently well dissipated by the void spaces within the target, such that these fragile ice structures respond as if they were strong in impacts. Therefore, it would appear that if EKOs are porous, they are not collisionally weak.

Also, our data show that collisional outcomes for low-velocity impacts into ice targets depend on the type of projectile used as well as the properties of the target. We observed that the degree of fragmentation for a given type of target increases as the strength of the projectile increases. Aluminum projectiles are far more damaging to the target at the same collisional energy than are solid ice projectiles, which, in turn, are more damaging than fractured ice projectiles. One possible explanation for this behavior is the variable depth of penetration of the projectile for the different cases — stronger projectiles penetrate more deeply and couple more energy into the target than do weak projectiles. Based on this, if we assume that there has not been significant heating or differentiation in the Edgeworth–Kuiper (E–K) belt, the most applicable impact strength for the low-velocity E–K belt collisions is likely to be that derived from similar target/projectile materials impacting each other. The laboratory data from this analysis indicate that a value for impact strength > 5 x 105 erg/cm3 is appropriate for porous ice targets impacted with solid/porous ice projectiles.

## 1999 Arakawa

29 April

### Collisional Disruption of Ice by High-Velocity Impact

#### Collision experiments (high velocity (2.3 – 4.7 km/s), -10°C, cubic ice targets (15 – 100 mm), nylon projectile (7 mg), mass ratio projectile/target: 10-6 – 10-3), results: shock pressure attenuates as (projectile size/propagation distance)2, irrespective of mass ratio, reaccumulation and escape conditions: large (radius > 20 k) icy bodies will reaccumulate and form rubble pile, small (radius < 2 km) icy bodies will never reaccumulate after catastrophic disruption (all fragments escape)

High-velocity impact among icy planetesimals is a physical phenomenon important to the planetary evolution process in the outer Solar System. In order to study this phenomenon, impact experiments on water ice were made by using a two-stage light gas gun installed in a cold room (-10°C) to clarify the elementary processes of collisional disruption and to study the reaccumulation and the escape conditions of the impact fragments. Cubic ice targets ranging in size from 15 to 100 mm were impacted by a nylon projectile of 7 mg with an impact velocity (vi) from 2.3 to 4.7 km/s. The corresponding mass ratio of the projectile to the target (mp/Mt) ranged from 10-3 to 10-6, which is two orders of magnitude lower than that used in previous studies (Arakawa et al. 1995, Icarus 118, 341–354). As a result, we obtained data on elementary processes such as attenuation of the shock wave and fragmentation dynamics. We found that the shock pressure attenuates in the ice target according to the relation of P~(Lp/r)2, irrespective of the mass ratio between 10-3 and 10-5, where Lp is the projectile size and r is a propagation distance. The largest fragment mass (ml) normalized by the original target mass has a good relationship to a nondimensional impact stress (PI, NDIS) defined as the ratio of the antipodal pressure to the material strength. This relationship is described as ml/Mt~PI-1.7 for a wide range of impact conditions (50 m/s < vi < 4 km/s and 10-1 < ml/Mt < 10-6), and shows the utility of NDIS. Using a measured shock wave decay constant of 2, the reaccumulation and the escape conditions of icy bodies in high-velocity collisions were estimated. As a result, it was clarified that a rubble pile could be formed when large icy bodies (radius > 20 km) reaccumulated. On the other hand, when smaller icy bodies (radius < 2 km) disrupted catastrophically, all fragments escaped and a rubble pile was never formed.

## 1998 Iedema

4 September , Dresser, Doering, Rowland, Hess, Tsekouras, Cowin

### Ferroelectricity in Water Ice

#### Characterisation experiments (partially proton-ordered ice Ic (vapour deposited on Pt(111) substrate), 40 – 150 K, Kelvin probe), result: slight preference for O aiming away from surface, 0.2 % net dipole per H2O molecule (@ 40 K) = -3 mV/monolayer, decreases with deposition T (exp(-T/27K)), when ice changes from amorphous to crystalline (130, 140, 150 K), dielectric properties become active, vapour-deposited ice in space may develop large electric fields

Partially proton-ordered ice I (cubic) was grown from the vapor phase, from 40 to nearly 150 K. It is believed to be metastable and oriented by the asymmetry of the solid-vacuum interface during growth. This was studied using a Kelvin (work function) probe for ice grown on a single-crystal Pt(111) substrate. The ice grows with a slight preference for the O-end aimed away from the surface, with about 0.2% net up dipole per water molecule at 40 K, or about -3 mV/monolayer of deposited ice film. This decreases with deposition temperature as exp(-T/27 K). Near 130, 140, and 150 K sharp features occur as the ice changes from amorphous to crystalline, and dielectric properties become active. By 150 K the effect seems to be zero. These results are discussed in context with other recent reports on ferroelectric ice. In addition to influencing several kinds of vacuum-based studies of ice, this slight ferroelectricity may allow natural ice vapor-grown in space to develop large electric fields.

## 1998 Higa

1 April , Arakawa, Maeno

### Size Dependence of Restitution Coefficients of Ice in Relation to Collision Strength

#### size dependence of COR, water ice spheres (1.4 – 36 mm), 1 – 1000 cm/s, 261 K, critical velocity

We have investigated the size dependence of the restitution coefficient (**) of a water ice sphere over a wide range of impact velocities (*v*i = 1–1000 cm/s) and radii (*r*p = 0.14–3.6 cm) at 261 K. The impact velocity dependence of ** was divided into two regions by the critical velocity (*v*c), which was the onset velocity of fracturing as well. In the quasi-elastic region (*v*i < *v*c), ** was almost constant and ice spheres did not fracture at all. In the inelastic region (*v*i ≥ *v*c), ** decreased with increasing *v*i and ice spheres fractured. **was then fitted as **(*v*i) = **qe (*v*i/*v*c)-log(*v*i/*v*c). The size dependencies of ** in both regions were different. In the quasi-elastic region, the average value of ** decreased with decreasing *r*p from **qe = 0.95 (*r*p = 3.6 cm) to **qe = 0.71 (*r*p = 0.14 cm). However, the maximum value of ** in this region was close to unity and irrespective of *r*p. In the inelastic region, ** increased with decreasing *r*p. *v*c was shown to increase with decreasing *r*p from 23 cm/s (*r*p = 3.6 cm) to 124 cm/s (*r*p = 0.14 cm). The size dependence of *v*c was explained by the strain-rate dependence of the fracture strength of ice.

## 1997 Supulver

### The Sticking Properties of Water Frost Produced under Various Ambient Conditions

#### water frost sticking properties, thin porous frost stickier than thick dense frost, temperature fluctuations increase stickiness, frost bond elastic (like spring), they suggest frost to be in proto-planetary nebulae

To form planetary systems, small solid particles which condense out of the cooling gas of the primitive solar nebula must aggregate together to form larger bodies. Centimeter-sized particles can grow out of micrometer-sized grains; planets can form from the coagulation of kilometer-sized planetesimals. The formation of stable, long-lived kilometer-sized objects from centimeter-sized particles is, however, not so straightforward. Some sort of surface sticking force is needed to hold these aggregates together against rotational forces as well as collisions in a turbulent solar nebula. We have performed experiments to determine the surface sticking force of water frosts under a variety of ambient conditions. Our primary results are listed below.

1. The structure of the frost is critical in determining its sticking properties; thin, porous frosts are more likely to adhere than are thick, dense frosts.

2. Sticking forces range up to 250 dyn/mm2.

3. Temperature fluctuations can increase the sticking force by significant amounts.

4. The frost bond acts like a spring: it stretches before breaking, with the displacement proportional to the applied force. Measured spring constants for many different water frosts cluster between 105 and 106 dyn/cm (over a total area of 78 mm2).

Based on these findings, we suggest that frosts of volatiles such as water could provide the necessary surface sticking mechanism in some low-temperature regions of the solar nebula.

## 1996 Dilley

25 April , Crawford

### Mass dependence of energy loss in collisions of icy spheres: An experimental study

#### collision experiments, ice spheres with ice blocks, ≈ 250 K, collisions become inelastic < 1 cm/s, elasticity decreases with decreasing mass

By varying the mass of icy spheres which collide with large ice blocks, we have determined the mass dependence of energy loss in such collisions. We find, at commercial deep freeze temperatures, that collisions at 1 cm/s become quite inelastic for small iceballs and that the rate at which elasticity decreases with decreasing mass roughly coincide with that predicted by a viscous dissipation model. If such a mass dependence persists at much lower temperatures, it could lead to very large effects in planetary ring systems (rings and dust, ice, surfaces, origin, and evolution).

## 1996 Bridges

12 February , Supulver, Lin, Knight, Zafra

### Energy Loss and Sticking Mechanisms in Particle Aggregation in Planetesimal Formation

#### Contact sticking experiments (surfaces coated with different types of frost, deposited at various low T and p) results: several frost coated surfaces stick together when brought into contact at ≈ 100 K, sticking force depends on deposition conditions, ice particles covered with H2O/CO2: sticking at low impact velocities, energy loss depends on v and surfaces structure, CH3OH: also effective sticky frost

A crucial step in the development of planetary systems is the aggregation of small solid particles to form planetesimals in gaseous protoplanetary disks such as the primordial solar nebula. Among small (centimeter-sized) aggregates for which self-gravity is negligible, a sticking mechanism is needed to hold the aggregate together, even when the relative velocities are very low. A similar cohesive process may also determine the size distribution of particles in planetary rings. In order to provide the crucial data, we carry out experiments to investigate the contact sticking that occurs for surfaces coated with different types of frosts, deposited at various (low) temperatures and pressures relevant to solar nebula conditions. Our preliminary measurements show that several types of frost-coated surfaces stick together when brought into contact at very low temperatures (≈ 100 K), but the sticking forces depend on the deposition conditions. For ice particles covered with H2O and CO2 frost: (1) the energy loss in collisions depends strongly on the impact speed and surface structure, and (2) particle ‘‘sticking’’ can occur if the impact speed is sufficiently low. Static sticking experiments using methanol (CH3OH) frost demonstrate that methanol is also an effective ‘‘sticky’’ frost. We apply these results to planetesimal formation and suggest that a layer of surface frost provides both the energy loss and the contact sticking required for the formation of large aggregates.

## 1996 Higa

6 October 1995 , Arakawa, Maeno

### Measurements of restitution coefficients of ice at low temperatures

#### COR const. (0.88), ice spheres 1.5 cm, 1 – 700 cm/s, 113 – 269 K

Measurements of the restitution coefficient (ε) of a smooth water ice sphere (radius = 1.5 cm) are made in a wide range of impact velocities (1 ≤ υi ≤ 700 cm s−1) and temperatures (113 ≤ T ≤ 269 K). The impact velocity dependence of ε is different in the quasi-elastic and inelastic regimes separated by a critical velocity (υc) at which fracture deformation occurs at the impact point of ice samples. In the quasi-elastic regime (υi ≤ υc), the value of ε is almost constant (0.88) and ice samples show no fracture deformations. In the inelastic regime (υi > υc), ε decreases with increasing υi and ice samples have fracture patterns. The velocity dependence of ε is fitted as ε(υi) = (υi υc)−log(υi υc). vc is shown to increase with decreasing temperature from 25 cm s−1 (269 K) to 180 cm s−1 (113 – 215 K).

## 1996 Arakawa

4 September 1995 , Higa

### Measurements of ejection velocities in collisional disruption of ice spheres

#### Collision experiments (ice spheres (projectile: 1.5 g, target: 1.5, 12, 172 g), reaccumulation, -18°C, 150 – 690 m/s), results: ejection velocity varies with initial position (3 – 110 x impact velocity), antipodal velocity varies with distance from impact point and with specific energy (1.7 – 2.9 x impact velocity)

Impact experiments are performed on ice spheres to measure the velocity field of ejected ice fragments and the conditions under which the fragments would reaccumulate during accretion in the outer solar system are considered. A single-stage light gas gun set in a cold room at −18°C and an image-converter camera running at 2 × 105-1 × 104 frames per second with a xenon flash lamp are used for observing the collisional phenomena. Spherical projectiles of ice (mp = 1.5 g) collide head-on with spherical targets (Mt = 1.5, 12, 172 g) at 150–690 m s−1. The ejection velocity is observed to vary with the initial position and ranges from 3 to 110 of the impact velocity (Vi). The ejection velocity of fragments at the rear side of the target (Ve) varies with distance from the impact point according to a power law relation, Ve = Va(l/D)−n, where Va is the antipodal velocity, l and D are the distance and the target diameter, and n = 1.5–2.0. Va depends on the specific energy (Q) at a constant mass ratio (mp/Mt = 0.13) and the empirical dependence is written as Va = 0.35 × Q0.52. The ejection velocity of fine fragments formed by the jetting process near the impact point is determined to be 1.7–2.9 times as large as the impact velocity irrespective of the target size and the impact velocity.

## 1995 Arakawa

12 June , Maeno, Higa, Iijima, Kato

### Ejection Velocity of Ice Impact Fragments

#### Collison experiments (ice, projectile on target impact, 30 – 530 m/s, mass ratio p/t = 0.1 to 0.0035), results: energy density (ice target begins to break up at 83 J/kg (5 times smaller than for basalt)), fragmentation strength, ejection velocity (2 times higher than for basalt), impact stress (decay constant decreases with increasing impact velocity)

Laboratory experiments on the impact disruption of ice were carried out to investigate the collisional phenomena of an icy planet. Ice projectiles were impacted on ice targets at impact velocities of 30 to 530 m/sec, and mass ratios of the projectile to the target of 0.1 to 0.0035. An ejection velocity at an antipodal point (Va) and a largest-fragment mass normalized by the target mass (ml/Mt) were used to examine two scaling parameters, an energy density (Q) and a nondimensional impact stress (Pl). The largest-fragment mass and the antipodal velocity have good correlations to Q but show apparent differences from a basalt target obtained by previous studies. The ice target begins to break up at 83 J/kg, which is two to five times smaller than for basalt. The ejection velocity is about two times higher than for basalt at the same Q. A modified nondimensional impact stress, P\*l , that involves a variable decay constant depending on the impact pressure is suggested. This eliminates the size dependence in the relation between Pl and the largest fragment. If we assume a simple relation to the antipodal velocity, Va /V\* = 2P\*l, where V\* is a characteristic velocity, the decay constant decreases with increasing impact velocity. The revised P\*l improved the relation between ml /Mt and the nondimensional impact stress. Ejection velocity in a center-of-mass frame was used to estimate a collisional condition for the icy planet to reaccumulate the disrupted fragments by planetary gravity.

## 1995 Kato

23 September 1994 , Iijima, Arakawa, Okimura, Fujimura, Maeno, Mizutani

### Ice-on-Ice Impact Experiments

#### Collision experiments (cratering & fragmentation, vertical gas gun, 255 K, projectiles: ice/aluminum, polycarbonate), results: mass distribution of fragments (power law, ice exponent bigger than for rock collisions, the same as found in Saturn’s rings => they probably originate from collisional disruption)

Impact experiments, cratering and fragmentation, on water ice were performed in order to test the scaling laws previously constructed on rocks and sands for studying the collision process in the planetary history. The installation of a vertical gas gun in a cold room at -18°C (255 K) made it possible to use a projectile of water ice and to get the detailed mass distribution of ice fragments. Experimental results indicated the necessity for large modification of those scaling laws. Material dependence was investigated by using projectiles of ice, aluminum, and polycarbonate. Differences were observed in the morphology and efficiencies of cratering and in the energies required to initiate the fragmentation. Moreover, an abrupt increase of cratering efficiency, suggesting a change of excavation mechanism, was found at a critical diameter of spalled crater. The mass (size) distribution of small ice fragments obeyed a power law with an exponent significantly larger than that in rocks. The exponent was the same as that in Saturn's ring particles estimated from the data by the microwave occultation, which indicates a collisional disruption ring origin.

## 1995 Supulver

19 September 1994 , Bridges, Lin

### The coefficient of restitution of ice particles in glancing collisions: Experimental results for unfrosted surfaces

#### Saturn’s rings, planetesimals disc, glancing collisions, COR components, spherical ice ball on long period pendulum, flat ice surface target, 100 K, smooth ice surface, room temperature collisions of rubber ball on rough surface (tangential friction force, highest energy loss at 45°-60° impact angle)

Both Saturn's rings and planetesimal disks are made up of particles in Keplerian orbits. Inelastic collisions between these particles regulate their dynamical evolution and possible aggregation. We present an experiment to simulate glancing collisions in Saturn's rings and in planetesimal disks and thus measure contributions to the energy loss for both normal and tangential velocity components. In this experiment, a spherical iceball mounted on a long-period, two dimensional pendulum is made to impact a flat ice surface in a low-temperature environment. This paper describes the experimental apparatus in detail and presents results for smooth unfrosted surfaces. The energy loss for tangential motion is surprisingly low, indicating that very little friction is present at low impact speeds for relatively smooth ice surfaces and temperatures near 100 K. We have also investigated room-temperature collisions of a rubber ball on a rough surface to understand the energy loss in situations where the tangential friction force is not small. In this analogous case, the energy loss is maximum for impact angles in the range 45°-60°.

## 1991 Hatzes

29 June 1990 , Bridges, Lin, Sachtjen

### Coagulation of Particles in Saturn's Rings: Measurements of the Cohesive Force of Water Frost

#### Collision experiments (sticking of frosted ice particles, frost layer 10 – 100 μm), results: no frost: cohesion force < 1 dyn, frost: cohesion force ≤ 100 dyn, dependent on impact velocity, cohesion maximal for intermediate v (≈ 0.1 cm/s), decreasing for smaller or larger velocities, spring constant of bond: 104 dyn, range of bond: 10 μm => ice particles should be able to survive tidal disruption when < 10 m

The cohesive properties of water ice particles may play an important role in the dynamics of ring particles as well as in the evolution of the particle size distribution. In this paper we present preliminary experimental data on the sticking force of water ice particles. The data indicate that the sticking force between smooth, frost-free ice particles is less than a dyne; however, the presence of a layer of water frost 10-100 μm thick on the ice surfaces increases this force up to 100 dyn. The resulting sticking force is dependent on the impact velocity of the particle and is maximized for some intermediate (≈ 0.1 cm/s) velocity. Consequently, a "Velcro" model is presented to describe the surface structure responsible for the sticking. The data indicate that there is a critical impact velocity of order 0.03 cm/s below which cohesion of particles always occurs. After sticking, the ice particle undergoes a damped harmonic motion characteristic of a linear force law having a range of order 10 μm. A spring constant of k ~ 104 dyn/cm is derived. We show that given the optical depth of micrometer-sized grains in Saturn's rings, particles are most likely coated with a significant layer of frost such that the cohesion of particles may be an important process in ring dynamics. Finally using the largest measured sticking forces we estimate the largest aggregate of ice particles capable of surviving tidal disruption to be about 10 m.

## 1989 McDonald

17 March , Hatzes, Bridges, Lin

### Mass transfer during ice particle collisions in planetary rings

#### Collision experiments (lab), result: 5 % of mass are exchanged, less than that are transferred

The collisional properties of ice particles determine the structure and dynamical evolution of planetary rings as well as the particle-size distribution. In this contribution, we present experimental data on the mass transfer during ice particle collisions in a laboratory environment which partially simulates the conditions in planetary rings. These data indicate that the interacting volume depends on the impact velocity. During a collision, the fraction of this volume exchanged is quite small, ∼5%; however, the net amount of material transferred may be considerably smaller. We discuss the possible implication of these data on the structure and dynamical evolution of planetary rings.

## 1989 Hallbrucker

8 February , Mayer, Johari

### The heat capacity and glass transition of hyperquenched glassy water

#### differential scanning calorimetry, 103 – 273 K, thermally reversible glass-liquid transition (Tg = 136 K, activation energy of structural relaxation ≈ 55 kJ/mol, transition width 12 K, increase in heat capacity = 1.6 kJ/mol), liquid water forms from glassy water at 146 K, crystallization near 232 K

The glass transition and heat capacity of hyperquenched glassy water have been studied by differential scanning calorimetry and by isothermal measurements from 103 K to a temperature where its crystallization to cubic ice is complete. Glassy water shows a thermally reversible glass-liquid transition and has a Tg, of 136 ± 1 K. The activation energy of structural relaxation in the transition range is ∼55kjmol−1 and is a reflection of the energy required to break two hydrogen bonds before a rotational-translational diffusion of a water molecule in the H-bonded network can occur. The temperature width of the transition is ∼12°, and the increase in the heat capacity is 1.6±0.1JK−1 mol−1. Liquid water formed on heating the glassy water to 146 K is more stable against crystallization than that which exists near 232 K. The hyperquenched glassy form of water can be thermodynamically continuous with liquid water, but whether or not it has the same structure as water above 273 K or supercooled water near the postulated γ-type transition is not known.

## 1988 Hatzes

### Collisional properties of ice spheres at low impact velocities

#### experiments, water ice spheres, disc pendulum, 85 K, 10-5 torr, COR:ε(v)= C exp (−γv), 0.015 – 2 cm/s, COR lowered by 10 – 30 % if surface rough/frosted, frost changes COR from exponential to power-law behaviour, application of results to Saturn’s rings

In this paper we discuss the results of our experimental studies on the impact properties of water ice. The measurements were made using a new apparatus consisting of a compound disc pendulum and a stainless steel, temperature controlled cryostat. With this apparatus we have been able to achieve stable temperatures of 85 K and pressures as low as 10−5 torr. Using a capacitive displacement device for accurately measuring the position of the pendulum during each collision, we have been able to obtain accurate measurements of the coefficient of restitution for ice spheres impacting with velocities in the range 0.015–2 cm s−1. The coefficient of restitution as a function of velocity, ε(*v*), for ice spheres with four different radii of curvature and with a variety of surface conditions has been obtained. The coefficient of restitution data can be well fitted by an exponential law of the form ε(*v*)= C exp (−γ*v*), for most measurements. We find, however, that the surface conditions can drastically alter the resulting value of ε. In particular the presence of frost or a roughened contact surface can lower ε at a given velocity by 10–30 per cent from that of a smooth sphere. We also show how the presence of frost can change the velocity behaviour of ε from an exponential to a power-law form. We briefly discuss the applications of our results to the dynamics of Saturn’s rings.

## 1987 Lange

15 October 1986 , Ahrens

### Impact Experiments in Low-Temperature Ice

#### Collision experiments (cubic & cylindrical ice targets (20 cm), 81 & 257 K, 100 – 640 m/s), results: crater diameters: 7 – 15 cm (2 – 3 x larger than for basalt at same conditions, 10 – 100 x larger than for crystalline rock), craters increase slightly with increasing target temperature

New results of low-velocity impact experiments in cubic and cylindrical (20 cm) water-ice targets initially at 257 and 81°K are reported. Impact velocities and impact energies vary between 0.1 and 0.64 km/sec and 109 and 1010 ergs, respectively. Observed crater diameters range from 7 to 15 cm and are two to three times larger than values found for equal-energy impacts in basaltic targets. Crater dimensions in ice targets increase slightly with increasing target temperatures. Crater volumes of strength-controlled ice craters are about 10 to 100 times larger than those observed for craters in crystalline rocks. Based on similarity analysis, general scaling laws for strength-controlled crater formation are derived and are applied to crater formation on the icy Galilean and Saturnian satellites. This analysis indicates that surface ages, based on impact-crater statistics on an icy crust, will appear greater than those for a silicate crust which experienced the same impact history. The greater ejecta volume for cratering in ice versus cratering in silicate targets leads to accelerated regolith production on an icy planet.

## 1984 Bridges

, Hatzes, Lin

### Structure, stability and evolution of Saturn’s rings

#### experiment results, COR of icy particles, Voyager spacecraft results, thickness of Saturn’s rings < 150 m, several ringlets (few m – 10 km radial dimension), some unstable to viscous diffusion -> optical depth variations

Recent data obtained from the Voyager spacecrafts and ground-based measurements indicate: (1) the rings have a thickness of at most 150 m (ref. 1) and probably several times less2,3; (2) the rings are mostly composed of ice particles ranging from centimetres to metres in size4; (3) the rings are subdivided into a large number of ringlets with a radial dimension ranging from 10 km down to the several metres resolution of the Voyager spacecraft's camera5; (4) the B ring contains very many optical depth variations (0.6–3)3. This behaviour is essentially determined by the collisional properties of the rings' ice particles. Here we report some preliminary results from an experiment designed to measure the coefficient of restitution of ice particles colliding at impact velocities relevant to Saturn's rings. We apply these results to simple dynamical models for Saturn's rings and deduce the rings' thickness to be < 5 m. We also show that regions with optical depth < 0.5, such as the B ring, are unstable to viscous diffusion. Such an instability may be the cause of optical depth variations in the B ring.

## 1983 Maeno

3 December 1982 , Ebinuma

### Pressure sintering of ice and its implication to the densification of snow at polar glaciers and ice sheets

#### Sintering experiments, six or more mechanisms contributing to neck growth simultaneously, review of pressureless sintering processes (vapour transport dominating, surface diffusion important in early stages), densification of snow = pressure sintering (takes into account three diffusional and dislocation creep mechanisms)

During the sintering of an aggregate of ice particles, six or more different mechanisms contribute simultaneously to the growth of necks formed between the particles. This paper reviews briefly the works on ice sintering carried out so far and discusses the discrepancies among them with reference to the pressureless sintering diagrams which show fields of dominance for each mechanism under a given physical condition. The vapor transport mechanism was concluded to be dominant in most natural and laboratory conditions, but in the very initial stage surface diffusion is also an important mechanism. Densification of natural snow can be interpreted adequately by regarding it a phenomenon of pressure sintering or hot pressing, which is driven not only by the excess surface free energy but also by the externally applied pressure. The construction of pressure sintering diagrams by taking into account of three diffusional and dislocation creep mechanisms has shown various useful applications to the study of snow densification at polar glaciers and in laboratory experiments of pressure sintering of ice compacts.

## 1982 Mayer

19 August , Brüggeller

### Vitrification of pure liquid water by high pressure jet freezing

#### produce vitrified (=glassy) water in a jet, compare X-ray diffraction patterns to vapour deposited ASW

The vitrification of pure liquid water by projecting a thin jet of liquid water at high speed into a liquid cryomedium is reported. The influence of the experimental parameters on the cooling rate and the devitrification of the jet-frozen vitrified material have been investigated. A structural difference between vitrified liquid water and amorphous solid water prepared from the vapour phase is inferred from a comparison of the X-ray diffraction patterns.

## 1982 Kuroda

18 July 1981 , Lacmann

### Growth kinetics of ice from the vapour phase and its growth forms

#### Theory, ice growing from vapour deposition, changes with temperature, -35°C – -4°C, vapour – quasi-liquid – solid mechanism / adhesive growth / 2D nucleation growth, type of surface structure (and thus growth mechanism) depends on surface orientation ({0001} or {1010} face) and temperature, spherical volume diffusion field near {0001} face, cylindrical volume diffusion field near {1010} face, surface diffusion from {0001} to {1010} faces

A new interpretation of the habits of ice growing from vapour is proposed. The basic habits of ice alternate three times: plates (A) → -4°C → columns (B) → -10°C → plates (C) → between -20°C and -35°C → columns (D). The theory is based on a viewpoint that the surface of ice just below 0°C is covered with a quasi-liquid layer, whose thickness δ or coverage ϑ decreases with falling temperature, and therefore the growth mechanism of a crystal face changes also as follows: (I) Vapour—Quasi-Liquid—Solid mechanism (ϑ > 1), (II) Adhesive Growth on a surface strongly adsorbed by H2O molecules (0.02 < ϑ < 1) and (III) Two- Dimensional Nucleation Growth on a surface with low eigen adsorption (ϑ < 0.02). The type of surface structure and consequently the growth mechanism depends on the surface orientation and the temperature. The complicated habit change is caused mainly by the combination of surface kinetics of the {0001} and {1010} face. The first and second conversion temperature (TAB, TBC) are expected to be independent of the absolute supersaturation ΔP as found in experiments. On the other hand, the third (TCD) is the temperature where the usual two-dimensional nucleation growth rate of the {0001} face reaches the one of the {1010} face, and exceeds it by the effect of diffusion field, so that the third conversion temperature falls with decreasing ΔP. The marked columnar crystals observed at -7°C can be explained only by taking into account the spherical volume diffusion field near the {0001} face and a cylindrical one near the {1010} face. For plate-like crystals between -10°C and -20°C to -35°C the surface diffusion from {0001} to {1010} and volume diffusion with cylindrical symmetry near {1010} faces is very important.

## 1964 Hobbs

2 November 1963 , Mason

### The Sintering and Adhesion of Ice

#### characterisation experiments (sintering (single and polycrystalline ice spheres (50 – 700 μm diameter), -3 – -20°C ), in air/hydrogen-gas/oil), results: evaporation-condensation theory valid (diffusion through environmental gas enhances neck growth), no evidence of liquid-like surface layer found unless surfaces are contaminated (e.g. by salts)

The current theory of sintering is incomplete and consequently previous experiments on the sintering of ice have been misinterpreted. The evaporation-condensation theory is now extended to include the case where material is transferred by diffusion through an environmental gas. Measurements were made on the rates of growth of the neck formed between single and polycrystalline ice spheres, 50 μ to 700 μ in diameter, in the temperature range -3°C to -20°C, in air at atmospheric pressure. The results are in quantitative agreement with the new evaporation-condensation theory, and further confirmation was obtained from experiments with spheres of heavy ice, and by the observed effects of replacing the air by either hydrogen or silicone oil. It is argued that the sintering of ice by either volume or surface diffusion would be slower by almost four orders of magnitude. No evidence is found for the recent suggestion that the sintering and adhesion of pure ice is caused by the existence of a liquid-like surface layer. The ice spheres show symptoms of having such a liquid layer only if they contain dissolved salts or if their surfaces are otherwise contaminated.

## 1961 Kuroiwa

30 March

### A Study of Ice Sintering

#### Characterization experiments (sintering (ice spheres < 200 µm diameter), in saturated air/kerosene environments), results: neck growth rate, ice-bonding (adhesion) is result of solid diffusion

Adhesion of ice, or ice-bonding phenomenon, at temperatures below 0°C was studied from the viewpoint of sintering. The growth rate of necks between ice spheres having radii R < 100 μ was measured in both saturated air and kerosene environments. The results showed that ice-bonding, or adhesion, takes place as a result of solid diffusion. Many photomicrographs of ice-bonds were taken by making use of thin-section technique.

# Dust + Ice

## 2017 Sirono

24 April , Ueno

### Collisions between Sintered Icy Aggregates

#### Numerical simulation: collisions of sintered icy dust aggregates, including temperature induced growth of sinter necks. Results: sintering strongly affects collisional growth, porous aggregates: critical velocity for growth 20 m/s (non-sintered 50 m/s), compact aggregates: main outcome is bouncing

Collisions between sintered icy dust aggregates are numerically simulated. If the temperature of an icy aggregate is sufficiently high, sintering promotes molecular transport and a neck between adjacent grains grows. This growth changes the mechanical responses of the neck. We included this effect in a simulation code, and conducted collisional simulations. For porous aggregates, the critical velocity for growth, below which the mass of an aggregate increases, decreased from 50 m s−1 for the non-sintered case to 20 m s−1. For compacted aggregates, the main collisional outcome is bouncing. These results come from the fact that the strength of the neck is increased by sintering. The numerical results suggest that the collisional growth of icy grain aggregates is strongly affected by sintering.

## 2015 Lorek

2 October , Gundlach, Lacerda, Blum

### Compaction of ice pebbles in collapsing pebble clouds and the dust-to-ice ratio of comets

#### Numerical model for comet formation (gravitational collapse of pebble (ice & silica) clouds, streaming instability), results: dust-to-ice ratio estimates for cometesimals

The gravitational collapse of pebble clouds formed in the streaming instability provides a mechanism for comet formation, which agrees well with the observed properties of comets, such as their low density. We numerically investigated the collapse of an ensemble of porous ice and silica pebbles and studied the final filling factor of these pebbles. Based on these results, we estimated the dust-to-ice ratio of the cometesimal and its dependency on initial conditions.

## 2014 Johansen

10 December , Blum, Tanaka, Ormel, Bizzarro, Rickman

### The multifaceted planetesimal formation process

#### hybrid model for planetesimal formation (particle growth starts unaided by self-gravity but later proceeds inside gravitationally collapsing pebble clumps to form planetesimals with a wide range of sizes)

Accumulation of dust and ice particles into planetesimals is an important step in the planet formation process. Planetesimals are the seeds of both terrestrial planets and the solid cores of gas and ice giants forming by core accretion. Left-over planetesimals in the form of asteroids, trans-Neptunian objects and comets provide a unique record of the physical conditions in the solar nebula. Debris from planetesimal collisions around other stars signposts that the planetesimal formation process, and hence planet formation, is ubiquitous in the Galaxy. The planetesimal formation stage extends from micrometer-sized dust and ice to bodies which can undergo run-away accretion. The latter ranges in size from 1 km to 1000 km, dependent on the planetesimal eccentricity excited by turbulent gas density fluctuations. Particles face many barriers during this growth, arising mainly from inefficient sticking, fragmentation and radial drift. Two promising growth pathways are mass transfer, where small aggregates transfer up to 50% of their mass in high-speed collisions with much larger targets, and fluffy growth, where aggregate cross sections and sticking probabilities are enhanced by a low internal density. A wide range of particle sizes, from mm to 10 m, concentrate in the turbulent gas flow. Overdense filaments fragment gravitationally into bound particle clumps, with most mass entering planetesimals of contracted radii from 100 to 500 km, depending on local disc properties. We propose a hybrid model for planetesimal formation where particle growth starts unaided by self-gravity but later proceeds inside gravitationally collapsing pebble clumps to form planetesimals with a wide range of sizes.

## 2014 Blum

8 March , Gundlach, Mühle, Trigo-Rodriguez

### Comets formed in solar-nebula instabilities! – An experimental and modeling attempt to relate the activity of comets to their formation process

#### Modelling and experiments on dust emission from comets etc., homogeneous layers of μm sized dust particles reach tensile strengths (103 – 104 Pa) far higher than water’s sublimation pressure, model of formation by gravitational instability leads to tensile strength of 1 Pa instead => could explain water driven comet activity (minimum size for dust-aggregates: ≈ 1 mm) => cometesimals must have formed by gravitational instability

When comet nuclei approach the Sun, the increasing energy flux through the surface layers leads to sublimation of the underlying ices and subsequent outgassing that promotes the observed emission of gas and dust. While the release of gas can be straightforwardly understood by solving the heat-transport equation and taking into account the finite permeability of the ice-free dust layer close to the surface of the comet nucleus, the ejection of dust additionally requires that the forces binding the dust particles to the comet nucleus must be overcome by the forces caused by the sublimation process. This relates to the question of how large the tensile strength of the overlying dust layer is. Homogeneous layers of micrometer-sized dust particles reach tensile strengths of typically 103 to 104 Pa. This exceeds by far the maximum sublimation pressure of water ice in comets. It is therefore unclear how cometary dust activity is driven. To solve this paradox, we used the model by Skorov and Blum (Skorov, Y.V., Blum, J. 2012. Icarus 221, 361–11), who assumed that cometesimals formed by gravitational instability of a cloud of dust and ice aggregates and calculated for the corresponding structure of comet nuclei tensile strength of the dust aggregate layers on the order of 1 Pa. Here we present evidence that the emitted cometary dust particles are indeed aggregates with the right properties to fit the model by Skorov and Blum. Then we experimentally measure the tensile strengths of layers of laboratory dust aggregates and confirm the values derived by the model. To explain the comet activity driven by the evaporation of water ice, we derive a minimum size for the dust aggregates of ≈ 1 mm, in agreement with meteoroid observations and dust-agglomeration models in the solar nebula. Finally we conclude that cometesimals must have formed by gravitational instability, because all alternative formation models lead to higher tensile strengths of the surface layers.

## 2014 Testi

, Birnstiel, Ricci, Andrews, Blum, Carpenter, Dominik, Isella, Natta, Williams, Wilner

### Dust Evolution in Protoplanetary Disks

#### Review: core accretion scenario, dust aggregate growth, last critical stages must happen in dense mid-plane -> observations at sub-mm – cm wavelengths required (ALMA), collision constraints (lab & modelling), dust settling, radial transport, global dust evolution models, migration/fragmentation barrier

In the core accretion scenario for the formation of planetary rocky cores, the first step toward planet formation is the growth of dust grains into larger and larger aggregates and eventually planetesimals. Although dust grains are thought to grow from the submicron sizes typical of interstellar dust to micron size particles in the dense regions of molecular clouds and cores, the growth from micron size particles to pebbles and kilometre size bodies must occur in the high densities reached in the mid-plane of protoplanetary disks. This critical step in the formation of planetary systems is the last stage of solids evolution that can be observed directly in young extrasolar systems before the appearance of large planetary-size bodies.

Tracing the properties of dust in the disk mid-plane, where the bulk of the material for planet formation resides, requires sensitive observations at long wavelengths (sub-mm through cm waves). At these wavelengths, the observed emission can be related to the dust opacity, which in turns depend on to the grain size distribution. In recent years the upgrade of the existing (sub-)mm arrays, the start of ALMA Early Science operations and the upgrade of the VLA have significantly improved the observational constraints on models of dust evolution in protoplanetary disks. Laboratory experiments and numerical simulations led to a substantial improvement in the understanding of the physical processes of grain-grain collisions, which are the foundation for the models of dust evolution in disks.

In this chapter we review the constraints on the physics of grain-grain collisions as they have emerged from laboratory experiments and numerical computations. We then review the current theoretical understanding of the global processes governing the evolution of solids in protoplanetary disks, including dust settling, growth, and radial transport. The predicted observational signatures of these processes are summarized.

We discuss the recent developments in the study of grain growth in molecular cloud cores and in collapsing envelopes of protostars as these likely provide the initial conditions for the dust in protoplanetary disks. We then discuss the current observational evidence for the growth of grains in young protoplanetary disks from millimeter surveys, as well as the very recent evidence of radial variations of the dust properties in disks. We also include a brief discussion of the constraints on the small end of the grain size distribution and on dust settling as derived from optical, near-, and mid-IR observations. The observations are discussed in the context of global dust evolution models, in particular we focus on the emerging evidence for a very efficient early growth of grains in disks and the radial distribution of maximum grain sizes as the result of growth barriers in disks. We will also highlight the limits of the current models of dust evolution in disks including the need to slow the radial drift of grains to overcome the migration/fragmentation barrier.

## 2013 Wada

5 September , Tanaka, Okuzumi, Kobayashi, Suyama, Kimura, Yamamoto

### Growth efficiency of dust aggregates through collisions with high mass ratios

#### Numerical simulation (collisions of different-sized icy dust aggregates), growth efficiency for nearly head-on collisions increases with size, growth efficiency increases with increasing mass ratio of colliding aggregates, growth possible at several 10 m/s for icy dust

*Context*. Collisional growth of dust aggregates is an essential process in forming planetesimals in protoplanetary disks, but disruption through high-velocity collisions (disruption barrier) could prohibit the dust growth. Mass transfer through very different-sized collisions has been suggested as a way to circumvent the disruption barrier.

*Aims*. We examine how the collisional growth efficiency of dust aggregates with different impact parameters depends on the size and the mass ratio of colliding aggregates.

*Methods*. We used an N-body code to numerically simulate the collisions of different-sized aggregates.

*Results*. Our results show that high values for the impact parameter are important and that the growth efficiency averaged over the impact parameter does not depend on the aggregate size, although the growth efficiency for nearly head-on collisions increases with size. We also find that the averaged growth efficiency tends to increase with increasing mass ratio of colliding aggregates. However, the critical collision velocity, above which the growth efficiency becomes negative, does not strongly depend on the mass ratio. These results indicate that icy dust can grow through high-velocity offset collisions at several tens of m s−1, the maximum collision velocity experienced in protoplanetary disks, whereas it is still difficult for silicate dust to grow in protoplanetary disks.

## 2013 Kataoka

, Tanaka, Okuzumi, Wada

### Fluffy dust forms icy planetesimals by static compression

#### analytical analysis of static compression (disk gas pressure and self gravity), coagulation forms fluffy grains, problem: collisions don’t compress them enough to from compact planetesimals, gas and self gravity can overcome this

*Context.* Several barriers have been proposed in planetesimal formation theory: bouncing, fragmentation, and radial drift problems. Understanding the structure evolution of dust aggregates is a key in planetesimal formation. Dust grains become fluffy by coagulation in protoplanetary disks. However, once they are fluffy, they are not sufficiently compressed by collisional compression to form compact planetesimals.

*Aims.* We aim to reveal the pathway of dust structure evolution from dust grains to compact planetesimals.

*Methods.* Using the compressive strength formula, we analytically investigate how fluffy dust aggregates are compressed by static compression due to ram pressure of the disk gas and self-gravity of the aggregates in protoplanetary disks.

*Results.* We reveal the pathway of the porosity evolution from dust grains via fluffy aggregates to form planetesimals, circumventing the barriers in planetesimal formation. The aggregates are compressed by the disk gas to a density of 10−3 g/cm3 in coagulation, which is more compact than is the case with collisional compression. Then, they are compressed more by self-gravity to 10−1 g/cm3 when the radius is 10 km. Although the gas compression decelerates the growth, the aggregates grow rapidly enough to avoid the radial drift barrier when the orbital radius is <∼6 AU in a typical disk.

*Conclusions.* We propose a fluffy dust growth scenario from grains to planetesimals. It enables icy planetesimal formation in a wide range beyond the snowline in protoplanetary disks. This result proposes a concrete initial condition of planetesimals for the later stages of the planet formation.

## 2013 Ros

### Ice condensation as a planet formation mechanism

#### numerical modeling, condensation (around snow line) can support/continue growth where dust coagulation is frustrated by barriers, growth from mm to decimeter scale in 1000 years, water transport over radial ice line dominant (over atmospheric ice line negligible), model ignores sticking/fragmenting particle collisions

We show that condensation is an efficient particle growth mechanism that leads to growth beyond decimetre-sized pebbles close to an ice line in protoplanetary discs. As coagulation of dust particles is frustrated by bouncing and fragmentation, condensation could be a complementary, or even dominant, growth mode in the early stages of planet formation. Ice particles diffuse across the ice line and sublimate, and vapour diffusing inwards across the ice line recondenses onto already existing particles, causing them to grow. We develop a numerical model of the dynamical behaviour of ice particles close to the water ice line, approximately 3 AU from the host star. Particles move with the turbulent gas, modeled as a random walk. They also sediment towards the midplane and drift radially towards the central star. Condensation and sublimation are calculated using a Monte Carlo approach. Our results indicate that, with a turbulent α-value of 0.01, growth from millimetre to at least decimetre-sized pebbles is possible on a time scale of 1000 years. We find that particle growth is dominated by ice and vapour transport across the radial ice line, with negligible growth caused by transport across the atmospheric ice line. Ice particles mix outwards by turbulent diffusion, leading to net growth across the entire cold region. The resulting particles are large enough to be sensitive to concentration by streaming instabilities, pressure bumps and vortices, which can cause further growth into planetesimals. In our model, particles are considered to be homogeneous ice particles. Considering the more realistic composition of ice condensed onto rocky ice nuclei might affect the growth time scales, by release of refractory ice nuclei after sublimation. We also ignore sticking and fragmentation in particle collisions. These effects will be the subject of future investigations.

## 2012 Suyama

### GEOMETRIC CROSS SECTIONS OF DUST AGGREGATES AND A COMPRESSION MODEL FOR AGGREGATE COLLISIONS

#### 3D N-body simulations (sequential collisions, aggregates composed of sub-micron-sized icy dust particles, coupling with disk gas, non-equal-mass/equal-mass collisions), insufficient compression -> remain fluffy

Geometric cross sections of dust aggregates determine their coupling with disk gas, which governs their motions in protoplanetary disks. Collisional outcomes also depend on geometric cross sections of initial aggregates. In a previous paper, we performed three-dimensional N-body simulations of sequential collisions of aggregates composed of a number of sub-micron-sized icy particles and examined radii of gyration (and bulk densities) of the obtained aggregates. We showed that collisional compression of aggregates is not efficient and that aggregates remain fluffy. In the present study, we examine geometric cross sections of the aggregates. Their cross sections decrease due to compression as well as to their gyration radii. It is found that a relation between the cross section and the gyration radius proposed by Okuzumi et al. is valid for the compressed aggregates. We also refine the compression model proposed in our previous paper. The refined model enables us to calculate the evolution of both gyration radii and cross sections of growing aggregates and reproduces well our numerical results of sequential aggregate collisions. The refined model can describe non-equal-mass collisions as well as equal-mass cases. Although we do not take into account oblique collisions in the present study, oblique collisions would further hinder compression of aggregates.

## 2012 Okuzumi

### RAPID COAGULATION OF POROUS DUST AGGREGATES OUTSIDE THE SNOW LINE: A PATHWAY TO SUCCESSFUL ICY PLANETESIMAL FORMATION

#### Model simulations (porosity change, submicron-sized icy dust aggregates, neglect fragmentation), result: internal densities << 0.1 g/cm3, overcome radial drift barrier at orbital radii < 10 AU

Rapid orbital drift of macroscopic dust particles is one of the major obstacles to planetesimal formation in protoplanetary disks. We re-examine this problem by considering the porosity evolution of dust aggregates. We apply a porosity model based on recent N-body simulations of aggregate collisions, which allows us to study the porosity change upon collision for a wide range of impact energies. As a first step, we neglect collisional fragmentation and instead focus on dust evolution outside the snow line, where the fragmentation has been suggested to be less significant than inside the snow line because of the high sticking efficiency of icy particles. We show that dust particles can evolve into highly porous aggregates (with internal densities of much less than 0.1 g cm−3) even if collisional compression is taken into account. We also show that the high porosity triggers significant acceleration in collisional growth. This acceleration is a natural consequence of the particles’ aerodynamical properties at low Knudsen numbers, i.e., at particle radii larger than the mean free path of the gas molecules. Thanks to this rapid growth, the highly porous aggregates are found to overcome the radial drift barrier at orbital radii less than 10 AU (assuming the minimum-mass solar nebula model). This suggests that, if collisional fragmentation is truly insignificant, formation of icy planetesimals is possible via direct collisional growth of submicron-sized icy particles.

## 2011 Aumatell

1 August

### Breaking the ice: planetesimal formation at the snowline

#### Lab experiments, sublimation of freely levitating ice aggregates, frequent break up, sublimation of drifting ice aggregates might locally increase the density of small dust (silicate)

Recently Saito & Sirono proposed that large ice aggregates which drift inwards in protoplanetary discs breakup during sublimation, ejecting embedded silicate particles. This would lead to a concentration of small solid particles close to the snowline. In view of this model, we carried out laboratory experiments where we observed freely levitating ice aggregates sublimating. We find that frequent breakup is indeed very common. Scaled to a 10 cm aggregate, about 2 × 104 small silicate aggregates might result. This supports the idea that sublimation of drifting ice aggregates might locally increase the density of small dust (silicate) particles which might more easily be swept up by larger dust aggregates or trigger gravitational instability. Either way, this might locally boost the formation of planetesimals at the snowline.

## 2011 Gundlach

2 May , Kilias, Beitz, Blum

### Micrometer-sized ice particles for planetary-science experiments –

### I. Preparation, critical rolling friction force, and specific surface energy

#### Characterisation of ice aggregates, built of μm-sized H2O ice particles (formed by spraying water into liquid N2), porosity of aggregates depends on production method: 0.11 – 0.72 volume filing factor, critical rolling friction force ice: 114.8 x 10-10 N (silica: 12.1 x 10-10 N), adhesive bonding for ice stronger than for SiO2, specific surface energy ice: 0.19 J/m2

Coagulation models assume a higher sticking threshold for micrometer-sized ice particles than for micrometer-sized silicate particles. However, in contrast to silicates, laboratory investigations of the collision properties of micrometer-sized ice particles (in particular, of the most abundant H2O -ice) have not been conducted yet. Thus, we used two different experimental methods to produce micrometer-sized H2O-ice particles, i.e. by spraying H2O droplets into liquid nitrogen and by spraying H2O droplets into a cold nitrogen atmosphere. The mean particle radii of the ice particles produced with these experimental methods are (1.49 ± 0.79) μm and (1.45 ± 0.65) μm. Ice aggregates composed of the micrometer-sized ice particles are highly porous (volume filling factor: φ = 0.11 ± 0.01) or rather compact (volume filling factor: φ = 0.72 ± 0.04), depending on the method of production. Furthermore, the critical rolling friction force of FRoll,ice = (114.8 ± 23.8) x 10-10 N was measured for micrometer-sized ice particles, which exceeds the critical rolling friction force of micrometer-sized SiO2 particles (FRoll,SiO2 = (12.1 ± 3.6) x 10-10 N). This result implies that the adhesive bonding between micrometer-sized ice particles is stronger than the bonding strength between SiO2 particles. An estimation of the specific surface energy of micrometer- sized ice particles, derived from the measured critical rolling friction forces and the surface energy of micrometer-sized SiO2 particles, results in γice = 0.190 J m-2.

## 2011 Sirono

29 April

### THE SINTERING REGION OF ICY DUST AGGREGATES IN A PROTOPLANETARY NEBULA

#### Sintering increases strength of neck in aggregates, sintering region can span whole nebula

Icy grain aggregates are formed in the outer region of a protoplanetary nebula. The infall of these aggregates to the central star is due to gas drag, and their temperature increases as the infall proceeds. The icy molecules on the grain move to the neck where the grains get connected through sublimation and condensation of the molecules. This process is called sintering. As the sintering proceeds, the mechanical strength of the neck changes considerably, strongly affecting the collisional evolution of the aggregates. The timescale required for sintering is determined in this study, based on which the region where the sintering proceeds within a prescribed timescale is obtained. It is found that the region covers a substantial fraction of the protoplanetary nebula, and the location of the region depends on the temperature distribution inside the nebula. If the aggregate is stirred up and the temperature of the aggregate increases temporally, the sintering region spreads to the whole nebula.

## 2011 Sirono

25 April

### Planetesimal formation induced by sintering

#### Numerical simulations (sintering of icy dust aggregates), accumulation of fragments in particular region of protoplanetary nebula, planetesimal formation by gravitational instability

Sintering of H2O ice proceeds in an icy dust aggregate as the temperature increases due to the infall to the central star. By numerical simulations, I show that fragmentation of the aggregate by sintering occurs at a particular region of a protoplanetary nebula. The fragments accumulate at the region because their infalling velocity is low. The dust surface density exceeds the critical surface density required for gravitational instability to form planetesimals.

## 2011 Saito

29 November 2010 , Sirono

### Planetesimal formation by sublimation

#### Modelling (infall of icy dust aggregates by gas drag => temperature increase => H2O sublimation inside snow line => ejection of silicate cores (slower infall than icy dust => accumulation => gravitational instability)

This paper proposes a scenario for the formation of rocky plantesimals. In this scenario, the infall of an icy dust aggregate to the central star occurs because of gas drag in the protoplanetary nebula. The temperature of the aggregate rises and H2O ice sublimates within the snow line. The silicate cores in a dust grain are ejected, following which sublimation occurs. Because the infall velocity of a silicate grain is much less than that of the original aggregate, the silicate cores stagnate in the sublimation region. We calculate the evolution of the dust surface density distribution of the silicate cores. It is shown that the surface density is increased by a factor of 10 or more, which is sufficient to trigger gravitational instability in ∼600 yr after the formation of ∼10 cm sized aggregates.

## 2010 Min

3 December 2010 , Dullemond, Kama, Dominik

### The thermal structure and the location of the snow line in the protosolar nebula: axisymmetric models with full 3-D radiative transfer

#### modeling H2O snowline in young solar nebula (optically thick), two opposite effects (shielding/viscous heating), snowline position sensitive to dust grain opacity/mass accretion rate of disk, compute abundances of ice/dust, jump in solid surface density at snowline (and where rocky planets formed) smaller than previously assumed

The precise location of the water ice condensation front (snow line) in the protosolar nebula has been a debate for a long time. Its importance stems from the expected substantial jump in the abundance of solids beyond the snow line, which is conducive to planet formation, and from the higher stickiness in collisions of ice-coated dust grains, which may help the process of coagulation of dust and the formation of planetesimals. In an optically thin nebula, the location of the snow line is easily calculated to be around 3 AU, subject to brightness variations of the young Sun. However, in its first 5 to 10 million years, the solar nebula was optically thick, implying a smaller snowline radius due to shielding from direct sunlight, but also a larger radius because of viscous heating. Several models have attempted to treat these opposing effects. However, until recently treatments beyond an approximate 1+1D radiative transfer were unfeasible. We revisit the problem with a fully self-consistent 3D treatment in an axisymmetric disk model, including a density-dependent treatment of the dust and ice sublimation. We find that the location of the snow line is very sensitive to the opacities of the dust grains and the mass accretion rate of the disk. We show that previous approximate treatments are quite efficient at determining the location of the snow line if the energy budget is locally dominated by viscous accretion. Using this result we derive an analytic estimate of the location of the snow line that compares very well with results from this and previous studies. Using solar abundances of the elements we compute the abundance of dust and ice and find that the expected jump in solid surface density at the snow line is smaller than previously assumed. We further show that in the inner few AU the refractory species are also partly evaporated, leading to a significantly smaller solid state surface density in the regions where the rocky planets were formed.

## 2009 Salter

13 July , Heißelmann, Chaparro, van der Wolk, Reißaus, Borst, Dawson, de Kuyper, Drinkwater, Gebauer, Hutcheon, Linnartz, Molster, Stoll, van der Tuijn, Fraser, Blum

### A zero-gravity instrument to study low velocity collisions of fragile particles at low temperatures

#### Collision experiments (microgravity (parabolic flight),, 0.03 – 0.28 m/s, 80 – 300 K), instrument description

We discuss the design, operation, and performance of a vacuum setup constructed for use in zero (or reduced) gravity conditions to initiate collisions of fragile millimeter-sized particles at low velocity and temperature. Such particles are typically found in many astronomical settings and in regions of planet formation. The instrument has participated in four parabolic flight campaigns to date, operating for a total of 2.4 h in reduced-gravity conditions and successfully recording over 300 separate collisions of loosely packed dust aggregates and ice samples. The imparted particle velocities achieved range from 0.03 to 0.28 m/s and a high-speed, high-resolution camera captures the events at 107 frames/s from two viewing angles separated by either 48.8° or 60.0°. The particles can be stored inside the experiment vacuum chamber at temperatures of 80–300 K for several uninterrupted hours using a built-in thermal accumulation system. The copper structure allows cooling down to cryogenic temperatures before commencement of the experiments. Throughout the parabolic flight campaigns, add-ons and modifications have been made, illustrating the instrument flexibility in the study of small particle collisions.

## 2009 Yasui

22 June , Arakawa

### Compaction experiments on ice-silica particle mixtures: Implication for residual porosity of small icy bodies

#### Compaction experiments (ice-silica mix, silica volume fractions 0 – 0.29, constant compression speed (0.2 / 2.0 mm/min), 263 K (30 MPa max compaction pressure) or 206 – 218 K (80 MPa max compaction pressure)), results: residual porosity larger for higher silica fractions (0.01 – 0.14 @(263 K & 30 MPa), 2 – 10 times larger @(206 – 218 K & 80 MPa)), model: predicts icy bodies < 700 km diameter to have residual porosity > 0.3 for T < 218 K.

To evaluate the residual porosity of small icy bodies, we performed compaction experiments on ice-silica mixtures and studied the effects of silica content, temperature, and compaction time scale on residual porosity. To simulate the compositions of real icy bodies, we used ice-silica mixtures with different silica volume fractions (0–0.29). The mixtures were compacted at a constant compression speed of 0.2 or 2.0 mm/min and the temperature was set to -10°C or a lower temperature (from -55 to -67°C). For the -10°C case, the mixtures were compressed to pressures of 30 MPa, while the lower temperature measurements were compressed to 80 MPa. In both cases, the residual porosity was found to be larger for higher silica fractions. At -10°C and 30 MPa, the residual porosity varied from 0.01 to 0.14 for silica fractions of 0–0.29, whereas for the -55 to -67°C and 80 MPa case, the corresponding residual porosities were 2–10 times larger. A two-layer model was proposed to calculate the compaction curves of ice-silica mixtures from the curves of the corresponding pure materials. We estimated the residual porosity of small icy bodies using this two-layer model. From our calculations, we expect that icy bodies with diameters smaller than 700 km have residual porosity larger than 0.3 when the temperature is lower than -55°C.

## 2008 Blum

, Wurm

### The Growth Mechanisms of Macroscopic Bodies in Protoplanetary Disks

#### Review of experimental achievements in context with protoplanetary disks, planetesimal formation: growth of fractal dust aggregates -> compaction -> mean velocity increases with increasing aggregate size -> stalling of growth / possible fragmentation (@ dm-sizes), hypotheses for further growth: sticky materials, secondary collision processes, enhanced growth at snow-line, cumulative dust effects, gravitational instability.

The formation of planetesimals, the kilometer-sized planetary precursors, is still a puzzling process. Considerable progress has been made over the past years in the physical description of the first stages of planetesimal formation, owing to extensive laboratory work. This review examines the experimental achievements and puts them into the context of the dust processes in protoplanetary disks. It has become clear that planetesimal formation starts with the growth of fractal dust aggregates, followed by compaction processes. As the dust-aggregate sizes increase, the mean collision velocity also increases, leading to the stalling of the growth and possibly to fragmentation, once the dust aggregates have reached decimeter sizes. A multitude of hypotheses for the further growth have been proposed, such as very sticky materials, secondary collision processes, enhanced growth at the snow line, or cumulative dust effects with gravitational instability. We will also critically review these ideas.

## 2008 Suyama

15 May , Wada

### NUMERICAL SIMULATION OF DENSITY EVOLUTION OF DUST AGGREGATES IN PROTOPLANETARY DISKS.

### I. HEAD-ON COLLISIONS

#### 3D N-body simulations (sequential collisions of aggregates composed of submicron-sized icy particles), density evolution/restructuring/compression, dust aggregates have extremely low density (<0.1 kg m-3)

The bulk density of dust aggregates is an important factor in collisional growth of dust in protoplanetary disks. The density of aggregates changes the coupling with the disk gas, which governs the motion of aggregates in disks. Collisional outcomes also depend on the aggregate density. We perform three-dimensional N-body simulations of sequential collisions of aggregates composed of a number of submicron-sized icy particles in order to investigate the density evolution of dust aggregates growing in protoplanetary disks. In the present simulation of sequential collisions, as the initial aggregates at each collision, we use the resultant aggregate obtained at the previous collision. By repeating N-body calculations of aggregate collisions, we examined the density evolution of aggregate collisions. At an early stage of dust growth, aggregates stick to each other without restructuring, and the density of these aggregates decreases. At a later stage, in which the impact energy exceeds a critical energy, aggregates are gradually compressed. The compressed aggregates have a fractal dimension of 2.5. Because of this small fractal dimension, their density remains very low even at this compression stage. We also derive an equation describing the density evolution of growing aggregates. Applying this equation to dust growth in protoplanetary disks, we find that dust aggregates have an extremely low density (<0.1 kg m-3). In the simulation of the present study, we consider only head-on collisions. The effect of oblique collisions would further reduce the aggregate density.

## 2007 Heißelmann

24 September , Fraser, Blum

### Experimental Studies on the Aggregation Properties of Ice and Dust in Planet-Forming Regions

#### Collision experiments (microgravity (parabolic flight), 0.1 – 0.5 m/s, dust / ice), instrument description, results: mostly bouncing, translational energy loss ≈ 95 %

To reveal the formation of planetesimals it is of great importance to understand the collision behavior of the dusty and icy aggregates they have formed from. We present an experimental setup to investigate the aggregation properties in low-velocity collisions of dust aggregates, solid ices and icy aggregates under microgravity conditions. Results from ESA's 45th Parabolic Flight Campaign show that most collisions in the velocity range 0.1 m/s ≤ vc ≤ 0.5 m/s are dominated by a rebound behavior of the projectile dust aggregates and only ~ 5% of the translational kinetic energy is conserved after the encounters.

## 2004 Arakawa

9 February , Tomizuka

### Ice–silicate fractionation among icy bodies due to the difference of impact strength between ice and ice–silicate mixture

#### Collision experiments (impact disruption of ice-silicate mixtures, silicate mass ratio 0 – 0.5, porosities: 0 – 37 %, 150 – 670 m/s), results: impact strength decreases with increasing porosity (mixture) / increases with porosity (pure H2O), higher silicate ratios enhanced strength

Laboratory experiments on the impact disruption of ice–silicate mixtures were conducted to clarify the accretion process of small icy bodies. Since the icy bodies are composed of ice and silicates with various porosities, we investigated the effect of porosity on the impact disruption of mixtures. We tested the mixture target with the mass ratio of ice to silicate, 0.5 and with 5 different porosities (0, 12.5, 25, 32, 37%) at the impact velocities of 150 to 670 m/s. The silicate mass ratio was changed from 0 to 0.5 in steps of 0.1 at a porosity of 12.5% and a constant impact velocity of about 300 m/s. The impact strength of the mixture was found to decrease with increasing porosity and the silicate mass ratio between 0.1 and 0.5 could enhance the strength of the icy target. The observed dependence of the impact strength on the porosity is opposite to that observed for pure ice. This difference could play an important role in ice–silicate fractionation during the accretion process. Because, ice rich bodies are easily broken as the porosity decreases in their evolution, the collisional growth could be prohibited. On the other hand, among the silicate rich bodies the collisional growth could be enhanced.

## 2003 Ehrenfreund

17 March , Fraser, Blum, Cartwright, García-Ruiz, Hadamcike, Levasseur-Regourd, Price, Prodi, Sarkissian

### Physics and chemistry of icy particles in the universe: answers from microgravity

#### cold ISM: dust particles covered in ultrathin icy layers, drive rich chemistry in star-forming regions, polar caps of terrestrial planets and outer solar system satellites covered in ice, earth atmosphere, weather etc., are lab ices good analogues?, bulk structure, surface catalytic properties, ice + dust experiments (1 + 0 g) + models, proposed experiments for ISS

During the last century, the presence of icy particles throughout the universe has been confirmed by numerous ground and space based observations. Ultrathin icy layers are known to cover dust particles within the cold regions of the interstellar medium, and drive a rich chemistry in energetic star-forming regions. The polar caps of terrestrial planets, as well as most of the outer-solar-system satellites, are covered with an icy surface. Smaller solar system bodies, such as comets and Kuiper Belt Objects (KBOs), contain a significant fraction of icy materials. Icy particles are also present in planetary atmospheres and play an important role in determining the climate and the environmental conditions on our host planet, Earth. Water ice seems universal in space and is by far the most abundant condensed-phase species in our universe. Many research groups have focused their efforts on understanding the physical and chemical nature of water ice. However, open questions remain as to whether ices produced in Earth’s laboratories are indeed good analogs for ices observed in space environments. Although temperature and pressure conditions can be very well controlled in the laboratory, it is very difficult to simulate the time-scales and gravity conditions of space environments. The bulk structure of ice, and the catalytic properties of the surface, could be rather different when formed in zero gravity in space.

The author list comprises the members of the ESA Topical Team: Physico-chemistry of ices in space. In this paper we present recent results including ground-based experiments on ice and dust, models as well as related space experiments performed under microgravity conditions. We also investigate the possibilities of designing a new infrastructure, and /or making improvements to the existing hardware in order to study ices on the International Space Station (ISS). The type of multidisciplinary facility that we describe will support research in crystal growth of ices and other solid refractory materials, aerosol microphysics, light scattering properties of solid particles, the physics of icy particle aggregates, and radiation processing of molecular ices. Studying ices in microgravity conditions will provide us with fundamental data on the nature of extraterrestrial ices and allow us to enhance our knowledge on the physical and chemical processes prevailing in different space environments.

## 2002 Arakawa

16 April , Leliwa-Kopystynski, Maeno

### Impact Experiments on Porous Icy-Silicate Cylindrical Blocks and the Implication for Disruption and Accumulation of Small Icy Bodies

#### Collision experiments (pure ice & ice-silica mix, porosity ≤ 55 %, 150 – 670 m/s, 263 K), results: maximum ejecta velocity (normalized by impact velocity) decreases with increasing porosity & is independent of material (mix), impact strength: pure ice: increase with increasing porosity, mixture: decrease with increasing porosity, three types of collisional outcome: mass loss, rubble pile formation, regolith formation (compaction)

Impact strength and cratering ejecta were studied for porous targets of pure ice and icy-silicate mixture in order to clarify the accumulation and destruction (shattering) condition of small icy bodies. The icy projectile impacted on the cylindrical targets with the porosity up to 55% at a velocity of 150 to 670 m/s at −10°C. The porosity dependence of the impact strength and that of the maximum ejecta velocity were measured in each type of these targets. As a result, the maximum ejecta velocity normalized by the impact velocity (Ve-max/Vi) is found to depend only on the porosity (φ), irrespective of the target type; a relationship is derived to be Ve-max/Vi=−2.17 φ +1.29. The impact strength of pure ice increased with increased target porosity, but that of mixture target had an opposite trend; that is, the strength decreased with increased porosity. These porosity dependencies of the impact strength could be explained by the porosity dependence of the physical parameters such as impact pressure, pressure decay, and static strength. Finally, the accumulation of small icy bodies is discussed to show that the collisional events can be divided into three types by the porosity and the collision velocity according to our experimental results: mass loss, rubble pile formation, and regolith formation (compaction).

## 1997 Dominik

9 December 1996 , Tielens

### The physics of dust coagulation and the structure of dust aggregates in space

#### Modelling (collisions of dust, ice + other materials), results: growth of aggregates by monomers normally not restructures them, hit-and-stick assumption reasonably valid, significant compaction in aggregate collisions, critical energies for different restructuring processes (help modelling), turbulence compresses aggregates

Even though dust coagulation is a very important dust-processing mechanism in interstellar space and protoplanetary disks, there are still important parts of the physics involved that are poorly understood. This imposes a serious problem for model calculations of any kind. In this paper, we attempt to improve the situation by including the effects of tangential forces on the contact in some detail. These have been studied in recent papers. We summarize the main results from these papers and apply them to detailed simulations of the coagulation process and of collisions between dust aggregates. Our results show the following: (1) the growth of aggregates by monomers will normally not involve major restructuring of the aggregates, (2) the classical *hit-and-stick* assumption is reasonably valid for this case, (3) collisions of aggregates with each other or with large grains can lead to significant compaction, and (4) the results can be easily understood in terms of critical energies for different restructuring processes. We also derive a short summary that may be used as a recipe for determining the outcome of collisions in coagulation calculations. It is shown that turbulent velocity fields in interstellar clouds are capable of producing considerably compressed aggregates, while the small aggregates forming early on in the solar nebula will not be compacted by collisions. However, compaction provides an important energy sink in collisions of larger aggregates in the solar nebula.

## 1997 Weidenschilling

31 January

### The Origin of Comets in the Solar Nebula: A Unified Model

#### Modelling (numerical simulation (growth of cometesimals), beginning with uniform mixture of microscopic grains in nebular gas, coagulation, settling => small aggregates in central plane, gas drag, radial motion, velocity dispersion prevents gravitational instability to grow bodies > 10 m), results: size-distribution of cometesimals shows narrow peak @ 10’s – 100’s m, resulting bodies have low mechanical strength, macroscopic voids, small scale porosity

Comets originated as icy planetesimals in the outer Solar System, as shown by dynamical studies and direct observation of objects in the Kuiper disk. Their nuclei have low strength consistent with “rubble pile” structure and inhomogeneities on scales of tens to hundreds of meters. These properties can be explained by their formation process in the solar nebula.

I present results of numerical simulation of the growth of cometesimals, beginning with a uniform mixture of microscopic grains in the nebular gas. Coagulation and settling yield a thin, dense layer of small aggregates in the central plane of the nebula. Shear between this layer and the pressure-supported gas produces turbulence that initially inhibits gravitational instability. Particles grow by collisional coagulation; relative velocities are dominated by radial motion due to orbital decay induced by gas drag. The radial velocity dispersion further delays gravitational instability until the mean particle size reaches tens of meters. Lack of damping in the swarm of macroscopic particles limits gravitational instability to large scales that do not allow collapse to solid bodies. Collisional coagulation is responsible for growth even after instability occurs.

The size distribution of cometesimals growing by drag-induced collisions develops a narrow peak in the range tens to hundreds of meters. This occurs because drag-induced velocities decrease with size in this range, while gravitational focusing is negligible. Impact velocities have a minimum at the transition from drag-driven to gravitational accretion at approximately kilometer sizes. Bodies accreted in this manner should have low mechanical strength and macroscopic voids in addition to small-scale porosity. They will be composed of structural elements having a variety of scales, but with some tendency for preferential sizes in the range ∼10–100 m. These properties are in good agreement with inferred properties of comets, which may preserve a physical record of their accretion.

## 1993 Weidenschilling

, Cuzzi

### Formation of planetesimals in the solar nebula

#### Book chapter (evolution of solid particles in solar nebula), bodies ≤ km: motion dominated by gas drag, planetesimals probably formed by coagulation of grain aggregates, collisions caused by differential settling, turbulence, gas drag, orbital decay, sticking mechanisms poorly understood, growth aided by concentration of larger bodies toward central plane, gravitational instability unlikely for particle layer formed by settling (turbulence prevents reaching critical density (independent of particle size)

This chapter describes the evolution of solid particles in the solar nebula (or other circumstellar disk). Motions of bodies ≤ km in size were dominated by gas drag rather than gravity. An original population of microscopic grains had to produce > km-sized planetesimals before gravitational accretion of planets could begin. Planetesimals probably formed by coagulation of grain aggregates that collided due to differential settling, turbulence, and drag-induced orbital decay. Growth of such aggregates depended on sticking mechanism and their mechanical properties, which are poorly understood. Their growth was aided by concentration of larger bodies toward the central plane of the disk. The nebula could remain optically thick during this process. It is unlikely that a particle layer formed by settling would undergo gravitational instability, as a small amount of turbulence (e.g., α ≈ 10-4 in a convective disk) would keep the particle layer from reaching the critical density. This conclusion is independent of the particle size, as even large bodies do not effectively decouple from the gas. Even in a laminar disk, shear in the particle layer would generate enough turbulence to keep it stirred up. This shear-induced turbulence produces complex flow patterns that could result in radial transport and size- sorting of particles.

## 1983 Lange

10 February , Ahrens

### The dynamic tensile strength of ice and ice-silicate mixtures

#### Characterization experiments (strain rate and dynamic tensile strength of ice and ice-silicate mixtures), results: strengths vary between 1.6 – 22 MPa, strength increases with increasing silicate content and with applied strain rate (10-2 – 104 s-1), strength-strain relation similar to other geological materials

We determined the dynamic tensile strength of ice and ice silicate mixtures at strain rates of ∼104 s−1. At these strain rates, ice has a tensile strength of ∼17 MPa, and ice-silicate mixtures with 5 and 30 wt % sand content have strengths of ∼20 and 22 MPa, respectively. These values lie significantly above tensile strengths of ∼1.6 MPa for ice and of ∼5−6 MPa for frozen silt, measured at strain rates of ∼10−2 to 100 s−1, but markedly below values found for a variety of rocks at comparable strain rates. Results of the present experiments are used to derive parameters for continuum fracturing models in icy media, which are used to determine relations between tensile strength and strain rate, and to predict stress and damage histories as well as size frequency distributions for ice and ice-silicate fragments. It is found that tensile strength σM is related to strain rate by σM ∝ ε0[0.25–0.3], similar to results obtained for other geological materials. The increase of small fragments relative to larger fragments with increasing strain rate, as predicted by the continuum model, is a result which parallels findings in laboratory impact experiments.

# Dust

## 2014 Deckers

1 December , Teiser

### Macroscopic dust in protoplanetary disks – from growth to destruction

#### Collisions experiments (small drop tower, p < 0.5 mbar, 6.68 m/s, agglomerates of quartz dust (irregularly shaped μm-sized grains), cm-sized projectile (volume filling factor 0.466, varying height, diameter, mass), dm-sized target (1.5 kg, 12 cm diameter and height, volume filling factor 0.44)), results: low collision energies: mass transfer to target, projectile destroyed, accretion efficiency decreasing with increasing obliquity and increasing difference in filling factor (projectile more compact than target), accretion efficiency increases with increasing collision energy until threshold (298 mJ), beyond threshold: catastrophic disruption of target -> critical fragmentation strength: 190 mJ/kg (larger than expected), mass distribution of fragments: more small fragments for higher collision energies, implication for planet formation: smaller particles couple better to gas-drag -> re-accretion more likely

The collision dynamics of dusty bodies are crucial for planetesimal formation. Decimeter agglomerates are especially important in the different formation models. Therefore, in continuation of our experiments on mutual decimeter collisions, we investigate collisions of centimeter onto decimeter dust agglomerates in a small drop tower under vacuum conditions (p ≤ 5 × 10−1 mbar) at a mean collision velocity of 6.68 ± 0.67ms−1. We use quartz dust with irregularly shaped micrometer grains. Centimeter projectiles with different diameters, masses, and heights are used, their typical volume filling factor is φp,m = 0.466 ± 0.02. The decimeter agglomerates have a mass of about 1.5 kg, a diameter and height of 12 cm, and a mean filling factor of φt,m = 0.44 ± 0.004. At lower collision energies, only the projectile gets destroyed and mass is transferred to the target. The accretion efficiency decreases with increasing obliquity and increasing difference in filling factor, if the projectile is more compact than the target. The accretion efficiency increases with increasing collision energy for collision energies under a certain threshold. Beyond this threshold at 298 ± 25 mJ, catastrophic disruption of the target can be observed. This corresponds to a critical fragmentation strength Q\* = 190 ± 16 mJ/kg, which is a factor of four larger than expected. Analyses of the projectile fragments show a power-law size distribution with an average exponent of −3.8 ± 0.3. The mass distributions suggest that the fraction of smallest fragments increases for higher collision energies. This is interesting for impacts of small particles on large target bodies within protoplanetary disks, as smaller fragments couple better to the surrounding gas and re-accretion by gas drag is more likely.

## 2014 Blum

5 June , Beitz, Bukhari, Gundlach, Hagemann, Heißelmann, Kothe, Schräpler, von Borstel, Weidling

### Laboratory Drop Towers for the Experimental Simulation of Dust-aggregate Collisions in the Early Solar System

#### Collision experiments (description of lab dropt towers for dust (≤ 10 cm, ≤ 70 % porosity) collisions (0.01 m/s ≤ v ≤ 10 m/s))

For the purpose of investigating the evolution of dust aggregates in the early Solar System, we developed two vacuum drop towers in which fragile dust aggregates with sizes up to ~10 cm and porosities up to 70% can be collided. One of the drop towers is primarily used for very low impact speeds down to below 0.01 m/sec and makes use of a double release mechanism. Collisions are recorded in stereo-view by two highspeed cameras, which fall along the glass vacuum tube in the center-of-mass frame of the two dust aggregates. The other free-fall tower makes use of an electromagnetic accelerator that is capable of gently accelerating dust aggregates to up to 5 m/sec. In combination with the release of another dust aggregate to free fall, collision speeds up to ~10 m/sec can be achieved. Here, two fixed high-speed cameras record the collision events. In both drop towers, the dust aggregates are in free fall during the collision so that they are weightless and match the conditions in the early Solar System.

## 2014 Kelling

10 March , Wurm, Köster

### EXPERIMENTAL STUDY ON BOUNCING BARRIERS IN PROTOPLANETARY DISKS

#### Long term lab experiments, interaction of 100 dust aggregated with each other (1 mm, mm/s – cm/s, 900 s duration, 105 collisions, 2000 analysed), sticking and fragmentation, no net growth, bouncing barrier is likely limit of self-consistent particle growth

For dust aggregates in protoplanetary disks, a transition between sticking and bouncing in individual collisions at mm to cm sizes has been observed in the past. This leads to the notion of a bouncing barrier for which growth gets stalled. Here, we present long-term laboratory experiments on the outcome of repeated aggregate collisions at the bouncing barrier. About 100 SiO2 dust aggregates 1 mm in size were observed interacting with each other. Collisions occurred within a velocity range from below mm s−1 up to cm s−1. Aggregates continuously interacted with each other over a period of 900 s. During this time, more than 105 collisions occurred. Nearly 2000 collisions were analyzed in detail. No temporal stable net growth of larger aggregates was observed even though sticking collision occurred. Larger ensembles of aggregates sticking together were formed but were disassembled again during further collisional evolution. The concept of a bouncing barrier supports the formation of planetesimals by seeded collisional growth, as well as by gravitational instability favoring a significant total mass being limited to certain size ranges. Within our parameter set, the experiments confirm that bouncing barriers are one possible and likely evolutionary limit of self-consistent particle growth.

## 2013 Seizinger

14 October , Krijt, Kley

### Erosion of dust aggregates

#### model (molecular dynamics, spherical grain interactions, visco-elastic damping force, different sample generation methods), visco-elastic damping crucial to reproduce lab-results, erosion at impact velocities > 5 m/s, compact aggregates harder to erode, increasing projectile size shifts erosion threshold to higher velocities

*Aims.* The aim of this work is to gain a deeper insight into how much different aggregate types are affected by erosion. Especially, it is important to study the influence of the velocity of the impacting projectiles. We also want to provide models for dust growth in protoplanetary disks with simple recipes to account for erosion effects.

*Methods.* To study the erosion of dust aggregates we employed a molecular dynamics approach that features a detailed micro-physical model of the interaction of spherical grains. For the first time, the model has been extended by introducing a new visco-elastic damping force, which requires a proper calibration. Afterwards, different sample generation methods were used to cover a wide range of aggregate types.

*Results.* The visco-elastic damping force introduced in this work turns out to be crucial to reproduce results obtained from laboratory experiments. After proper calibration, we find that erosion occurs for impact velocities of 5 ms−1 and above. Though fractal aggregates as formed during the first growth phase are most susceptible to erosion, we observe erosion of aggregates with rather compact surfaces as well.

*Conclusions.* We find that bombarding a larger target aggregate with small projectiles results in erosion for impact velocities as low as a few ms−1. More compact aggregates suffer less from erosion. With increasing projectile size the transition from accretion to erosion is shifted to higher velocities. This allows larger bodies to grow through high velocity collisions with smaller aggregates.

## 2013 Meisner

14 October , Wurm, Teiser, Schywek

### Preplanetary scavengers: Growing tall in dust collisions

#### lab experiments, self-consistent evolution of dust target under continuous impact of sub-mm dust aggregates (71 m/s) -> mass gain of target, accretion efficiency decreasing with increasing velocity, projectile-mass dependent, target volume filling factor stabilizes at 38 %, large bodies can grow further by sweeping up smaller ones (high efficiency)

Dust collisions in protoplanetary disks are one means to grow planetesimals, but the destructive or constructive nature of high speed collisions is still unsettled. In laboratory experiments, we study the self-consistent evolution of a target upon *continuous* impacts of submm dust aggregates at collision velocities of up to 71 m/s. Earlier studies analyzed *individual* collisions, which were more speculative for high velocities and low projectile masses. Here, we confirm earlier findings that high speed collisions result in mass gain of the target. We also quantify the accretion efficiency for the used SiO2 (quartz) dust sample. For two different average masses of dust aggregates (0.29 μg and 2.67 μg) accretion efficiencies are decreasing with velocity from 58% to 18% and from 25% to 7% at 27 m/s to 71 m/s, respectively. The accretion efficiency decreases approximately as logarithmic with impact energy. At the impact velocity of 49 m/s the target acquires a volume filling factor of 38%. These data extend earlier work that pointed to the filling factor leveling off at 8 m/s to a value of 33%. Our results imply that high speed collisions are an important mode of particle evolution. It especially allows existing large bodies to grow further by scavenging smaller aggregates with high efficiency.

## 2013 Hirashita

14 June , Li

### Condition for the formation of micron-sized dust grains in dense molecular cloud cores

#### Numerical modelling (formation of μm-sized grains in dense cores of molecular clouds), results: coreshine (mid-IR emission due to scattering from μm-sized grains in dense cores) must come from long-lived entities rather than dynamically transient objects (based on free-fall time for typical hydrogen densities around 105 cm-3)

We investigate the condition for the formation of micron-sized grains in dense cores of molecular clouds. This is motivated by the detection of mid-infrared emission from deep inside a number of dense cores, the so-called ‘coreshine,’ which is thought to come from scattering by micron (μm)-sized grains. Based on numerical calculations of coagulation starting from the typical grain-size distribution in the diffuse interstellar medium, we obtain a conservative lower limit to the time t to form μm-sized grains: t/tff > 3(5/S)(nH/105 cm−3)−1/4 (where tff is the free-fall time at hydrogen number density nH in the core and S the enhancement factor of the grain–grain collision cross-section to account for non-compact aggregates). At the typical core density nH = 105 cm−3, it takes at least a few free-fall times to form the μm-sized grains responsible for coreshine. The implication is that those dense cores observed in coreshine are relatively long-lived entities in molecular clouds, rather than dynamically transient objects that last for one free-fall time or less.

## 2013 Kothe

20 February , Blum, Weidling, Güttler

### Free collisions in a microgravity many-particle experiment.

### III. The collision behavior of sub-millimeter-sized dust aggregates

#### microgravity experiments, collisions of sub-mm dust agglomerates (from m monomer grains), internal structure studied by X-ray CT before experiments -> no rim compaction -> no preparation artifacts, shallow power-law relation between aggregate mass and bouncing barrier velocity, no sharp transition sticking/bouncing, aggregates-of-aggregates stick at higher velocities than homogeneous agglomerates

We conducted micro-gravity experiments to study the outcome of collisions between sub-mm-sized dust agglomerates consisting of m-sized SiO2 monomer grains at velocities of several cm s-1. Prior to the experiments, we used X-ray computer tomography (nano-CT) imaging to study the internal structure of these dust agglomerates and found no rim compaction so that their collision behavior is not governed by preparation-caused artefacts. We found that collisions between these dust aggregates can lead either to sticking or to bouncing, depending mostly on the impact velocity. While previous collision models derived the transition between both regimes from contact physics, we used the available empirical data from these and earlier experiments to derive a power law relation between dust-aggregate mass and impact velocity for the threshold between the two collision outcomes. In agreement with earlier experiments, we show that the transition between both regimes is not sharp, but follows a shallower power law than predicted by previous models (Güttler, C., Blum, J., Zsom, A., Ormel, C.W., Dullemond, C.P. [2010]. Astron. Astrophys. 513, A56). Furthermore, we find that sticking between dust aggregates can lead to the formation of larger structures. Collisions between aggregates-of-aggregates can lead to growth at higher velocities than homogeneous dust agglomerates.

## 2013 Garaud

### FROM DUST TO PLANETESIMALS: AN IMPROVED MODEL FOR COLLISIONAL GROWTH IN PROTOPLANETARY DISKS

#### modelling, velocity distribution includes deterministic motion (from the vertical settling, radial drift, and azimuthal drift) and stochastic motion (from Brownian motion and turbulence), suggest they can thereby overcome bouncing barrier, grow large planetesimals and keep up significant population of small (m) grains

Planet formation occurs within the gas- and dust-rich environments of protoplanetary disks. Observations of these objects show that the growth of primordial submicron-sized particles into larger aggregates occurs at the earliest evolutionary stages of the disks. However, theoretical models of particle growth that use the Smoluchowski equation to describe collisional coagulation and fragmentation have so far failed to produce large particles while maintaining a significant population of small grains. This has generally been attributed to the existence of two barriers impeding growth due to bouncing and fragmentation of colliding particles. In this paper, we demonstrate that the importance of these barriers has been artificially inflated through the use of simplified models that do not take into account the stochastic nature of the particle motions within the gas disk. We present a new approach in which the relative velocities between two particles are described by a probability distribution function that models both deterministic motion (from the vertical settling, radial drift, and azimuthal drift) and stochastic motion (from Brownian motion and turbulence). Taking both into account can give quite different results to what has been considered recently in other studies. We demonstrate the vital effect of two “ingredients” for particle growth: the proper implementation of a velocity distribution function that overcomes the bouncing barrier and, in combination with mass transfer in high-mass-ratio collisions, boosts the growth of larger particles beyond the fragmentation barrier. A robust result of our simulations is the emergence of two particle populations (small and large), potentially explaining simultaneously a number of longstanding problems in protoplanetary disks, including planetesimal formation close to the central star, the presence of millimeter- to centimeter-sized particles far out in the disk, and the persistence of μm-sized grains for millions of years.

## 2012 Tanaka

, Wada, Suyama, Okuzumi

### Growth of Cosmic Dust Aggregates and Re-examination of Particle Interaction Models

#### molecular dynamics simulation of particle collisions, dust growth

Dust growth is the first step of planet formation in protoplanetary disks. Dust growth also influences the temperature of protoplanetary disks. However, we still have a large uncertainty in the dust growth process. This uncertainty mainly comes from unknown factors in dust internal structure and collisional outcomes. The dust structure and the collisional outcome would be closely related with each other. In recent years, many theoretical studies on aggregate collisions and growth have been done. In the present paper, we introduce remarkable results in these theoretical studies, mainly focusing on numerical simulations of dust collisions by our group. In the numerical simulations of dust collisions, we adopt the interaction model between constituent particles of dust aggregates. We have started the re-examination of the particle interaction model, by performing molecular dynamics simulation of particle collisions. We also report the preliminary results of our molecular dynamics simulations.

## 2012 Schräpler

14 August , Blum, Seizinger, Kley

### The physics of protoplanetesimal dust agglomerates.

### VII. The low-velocity collision behaviour of large dust agglomerates

#### Microgravity collision experiments (macroscopically homogeneous dust agglomerates of μm-sized silica particles, volume filling factors: 0.3 & 0.4, size: 5 cm, impact velocities: 0.01 – 0.5 m/s), COR + fragmentation velocity measured, ε(v): low v – ε decreases with increasing v, then constant, then onset of fragmentation, interpretation: transition from solid-body-dominated to granular-medium-dominated behaviour, molecular dynamics simulation to model experimental results, extension of earlier work (improved measurements, better statistics, theoretical approach), applications: protoplanetary disks, debris disks, planetary rings

We performed micro-gravity collision experiments in our laboratory drop tower using 5 cm sized dust agglomerates with volume filling factors of 0.3 and 0.4, respectively. This work is an extension of our previous experiments reported in Beitz et al. to aggregates of more than one order of magnitude higher masses. The dust aggregates consisted of micrometer-sized silica particles and were macroscopically homogeneous. We measured the coefficient of restitution for collision velocities ranging from 1 cm/s to 0.5 m/s, and determined the fragmentation velocity. For low velocities, the coefficient of restitution decreases with increasing impact velocity, in contrast to findings by Beitz et al. At higher velocities, the value of the coefficient of restitution becomes constant, before the aggregates break at the onset of fragmentation. We interpret the qualitative change in the coefficient of restitution as the transition from a solid-body-dominated to a granular-medium-dominated behavior. We complement our experiments by molecular-dynamics simulations of porous aggregates and obtain a reasonable match to the experimental data. We discuss the importance of our experiments for protoplanetary disks, debris disks, and planetary rings. This work is an extension to the previous work of our group and gives new insight into the velocity dependency of the coefficient of restitution due to improved measurements, better statistics, and a theoretical approach.

## 2012 Windmark

30 July , Birnstiel, Ormel, Dullemond

### Breaking through: The effects of a velocity distribution on barriers to dust growth

#### model, dust growth, effect of probability distribution on growth barriers (bouncing/fragmentation) -> barriers not sharp, small fraction of particles manage to grow orders of magnitude above the main population, velocity distribution softens fragmentation barrier + removes bouncing barrier, broadens size distribution -> seeds for sweep-up

*Context.* It is unknown how far dust growth can proceed by coagulation. Obstacles to collisional growth are the fragmentation and bouncing barriers. However, in all previous simulations of the dust-size evolution, only the mean collision velocity has been considered, neglecting that a small but possibly important fraction of the collisions will occur at both much lower and higher velocities.

*Aims.* We study the effect of the probability distribution of impact velocities on the collisional dust growth barriers.

*Methods.* We assume a Maxwellian velocity distribution for colliding particles to determine the fraction of sticking, bouncing, and fragmentation, and implement this in a dust-size evolution code. We also calculate the probability of growing through the barriers and the growth timescale in these regimes.

*Results.* We find that the collisional growth barriers are not as sharp as previously thought. With the existence of low-velocity collisions, a small fraction of the particles manage to grow to masses orders of magnitude above the main population.

*Conclusions.* A particle velocity distribution softens the fragmentation barrier and removes the bouncing barrier. It broadens the size distribution in a natural way, allowing the largest particles to become the first seeds that initiate sweep-up growth towards planetesimal sizes.

## 2012 Seizinger

11 March , Speith, Kley

### Compression behavior of porous dust agglomerates

#### Modelling (molecular dynamics approach to include normal forces, rolling, twisting and sliding between dust grains), aim: improve model for interaction of individual monomers to determine threshold between growth and destruction

*Context*. The early planetesimal growth proceeds through a sequence of sticking collisions of dust agglomerates. Very uncertain is still the relative velocity regime in which growth rather than destruction can take place. The outcome of a collision depends on the bulk properties of the porous dust agglomerates.

*Aims*. Continuum models of dust agglomerates require a set of material parameters that are often difficult to obtain from laboratory experiments. Here, we aim at determining those parameters from ab initio molecular dynamics simulations. Our goal is to improve on the existing model that describe the interaction of individual monomers.

*Methods*. We use a molecular dynamics approach featuring a detailed micro-physical model of the interaction of spherical grains. The model includes normal forces, rolling, twisting and sliding between the dust grains. We present a new treatment of wall-particle interaction that allows us to perform customized simulations that directly correspond to laboratory experiments.

*Results*. We find that the existing interaction model by Dominik & Tielens leads to a too soft compressive strength behavior for uni- and omni-directional compression. Upon making the rolling and sliding coefficients stiffer we find excellent agreement in both cases. Additionally, we find that the compressive strength curve depends on the velocity with which the sample is compressed.

*Conclusions*. The modified interaction strengths between two individual dust grains will lead to a different behavior of the whole dust agglomerate. This will influences the sticking probabilities and hence the growth of planetesimals. The new parameter set might possibly lead to an enhanced sticking as more energy can be stored in the system before breakup.

## 2012 Windmark

16 January , Birnstiel, Güttler, Blum, Dullemond, Henning

### Planetesimal formation by sweep-up: how the bouncing barrier can be beneficial to growth

#### dust collision model based on lab experiments (fragmentation with mass transfer -> growth at high impact velocities), cratering + mass transfer, smooth transition from equal to different-sized collisions, few cm-sized grains can act as catalyst for sticking and sweep up smaller particles (3 AU -> 100 m sized objects form in 1 Myr), bouncing barrier in this scenario beneficial (prevents growth of too many cm sized particles, maintains reservoir of small ones to be swept up), BUT few cm-sized particles have to be produced somehow to start with

*Context.* The formation of planetesimals is often accredited to the collisional sticking of dust grains. The exact process is unknown, as collisions between larger aggregates tend to lead to fragmentation or bouncing rather than sticking. Recent laboratory experiments have however made great progress in the understanding and mapping of the complex physics involved in dust collisions.

*Aims.* We study the possibility of planetesimal formation using the results of the latest laboratory experiments, particularly by including the *fragmentation with mass transfer* effect, which might lead to growth even at high impact velocities.

*Methods.* We present a new experimentally and physically motivated dust collision model capable of predicting the outcome of a collision between two particles of arbitrary mass and velocity. The new model includes a natural description of cratering and mass transfer, and provides a smooth transition from equal- to different-sized collisions. It is used together with a continuum dust-size evolution code, which is both fast in terms of execution time and able to resolve the dust at all sizes, allowing for all types of interactions to be studied without biases.

*Results.* For the general dust population, we find that bouncing collisions prevent any growth above millimeter-sizes. However, if a small number of cm-sized particles are introduced, for example by either vertical mixing or radial drift, they can act as a catalyst and start to sweep up the smaller particles. At a distance of 3 AU, 100-m-sized bodies are formed on a timescale of 1 Myr.

*Conclusions.* Direct growth of planetesimals might be a possibility thanks to a combination of the bouncing barrier and the fragmentation with mass transfer effect. The bouncing barrier is here even beneficial, as it prevents the growth of too many large particles that would otherwise only fragment among each other, and creates a reservoir of small particles that can be swept up by larger bodies. However, for this process to work, a few seeds of cm-size or larger have to be introduced.

## 2012 Perry

15 December 2011 , Gostomski, Matthews, Hyde

### The influence of monomer shape on aggregate morphology

#### influence of monomer shape (prolate ellipsoidal/spherical) on morphology of dust aggregates, particle-cluster aggregation vs. cluster-cluster aggregation, shape and aggregation mechanism influence compactness (8 – 80 %) and friction times, aggregates of spherical particles may not be good analogues for ISM dust

*Context.* The coagulation of dust particles is the initial step in planetary formation, with the precursors to planetesimals believed to form via the collisions of micron and submicron sized dust particles in the disk surrounding a newly formed protostar. One of the usual assumptions in numerical models of aggregation is that of spherical monomers. However, the polarization of light in the interstellar medium (ISM) indicates that dust particles may not necessarily be spherical.

*Aims.* This study investigates the influence of monomer shape (ellipsoidal vs. spherical) on the morphology of aggregates. The ellipsoidal grains used are prolate with an axis ratio of 3:1:1, which current evidence suggests as a possible shape for instellar dust grains.

*Methods.* Populations of aggregates are built from ellipsoidal monomers and spherical monomers using both particle-cluster aggregation (PCA) and cluster-cluster aggregation (CCA) regimes incorporating the rotation of particles. The morphology of the resulting aggregates is compared using the maximum radius, porosity, fractal dimension, compactness factor and friction time. The last two factors indicate how the dynamics of a population of dust may be altered depending on monomer shape.

*Results.* The results of this study indicate that monomer shape plays an important role in determining the final morphology of aggregates. Comparing ellipsoid grains with 3:1:1 axis ratio to spheres, the greatest difference is seen in compactness factors: (∼18%) for the PCA regime, reaching a maximum of (∼80%) for the CCA regime. The influence on porosity is also appreciable, (∼8%) and (∼15%) for PCA and CCA regimes respectively. The resulting differences for the friction times depend on the collision regime employed, yet show a marked difference for the different monomer shapes, (∼12%) for PCA and (>50%) for CCA at large sizes. It is concluded that the effect of monomer shape in the hit-and-stick aggregation model may produce appreciable structural variation in the final aggregate. Present models of fluffy aggregates made up of only spherical monomers therefore may not be the best representation for grains in some astrophysical environments.

## 2012 Min

4 November 2011 , Canovas, Mulders, Keller

### The effects of disk and dust structure on observed polarimetric images of protoplanetary disks

#### modelling (understand effects of dust particle structure/size-dependent grain settling/instrumental properties), different dust particle models and disk structures, particle size and shape have strong effect on brightness/detectability of disk, realistic models give very different results than homogeneous sphere model, need to also simulate telescope effects before interpretation of results

*Context.* Imaging polarimetry is a powerful tool for imaging faint circumstellar material. It is a rapidly developing field with great promise for diagnostics of both the large-scale structures and the small-scale details of the scattering particles.

*Aims.* For a correct analysis of observations we need to fully understand the effects of dust particle parameters, as well as the effects of the telescope, atmospheric seeing, and assumptions about the data reduction and processing of the observed signal. Here we study the major effects of dust particle structure, size-dependent grain settling, and instrumental properties.

*Methods.* We performed radiative transfer modeling using different dust particle models and disk structures. To study the influence of seeing and telescope diffraction we ran the models through an instrument simulator for the ExPo dual-beam imaging polarimeter mounted at the 4.2 m *William Herschel* Telescope (WHT).

*Results.* Particle shape and size have a strong influence on the brightness and detectability of the disks. In the simulated observations, the central resolution element also contains contributions from the inner regions of the protoplanetary disk besides the unpolarized central star. This causes the central resolution element to be polarized, making simple corrections for instrumental polarization difficult. This effect strongly depends on the spatial resolution, so adaptive optics systems are needed for proper polarization calibration.

*Conclusions.* We find that the commonly employed homogeneous sphere model gives results that differ significantly from more realistic models. For a proper analysis of the wealth of data available now or in the near future, one must properly take the effects of particle types and disk structure into account. The observed signal depends strongly on the properties of these more realistic models, thus providing a potentially powerful diagnostic. We conclude that it is important to correctly understand telescope depolarization and calibration effects for a correct interpretation of the degree of polarization.

## 2012 Weidling

14 October 2011 , Güttler, Blum

### Free collisions in a microgravity many-particle experiment.

### I. Dust aggregate sticking at low velocities

#### sticking threshold velocity of mm dust aggregates could not be reached in the lab so far -> microgravity experiments (> 0.1 cm/s, 0.5 – 2 mm), sticking for few collisions (0.2 – 3 cm/s) -> no sharp bouncing barrier, dust collision model -> deduced velocity below dust will always stick (8 x 10-5 m/s for mm dust)

Over the past years the processes involved in the growth of planetesimals have extensively been studied in the laboratory. Based on these experiments, a dust-aggregate collision model was developed upon which computer simulations were based to evaluate how big protoplanetary dust aggregates can grow and to analyze which kinds of collisions are relevant in the solar nebula and are worth further studies in the laboratory. The sticking threshold velocity of millimeter-sized dust aggregates is one such critical value that have so far only theoretically been derived, as the relevant velocities could not be reached in the laboratory. We developed a microgravity experiment that allows us for the first time to study free collisions of mm-sized dust aggregates down to velocities of ≈ 0.1 cm s-1 to assess this part of the proto- planetary dust evolution model. Here, we present the results of 125 free collisions between dust aggregates of 0.5–2 mm diameter. Seven collisions with velocities between 0.2 and 3 cm s-1 led to sticking, suggesting a transition from perfect sticking to perfect bouncing with a certain sticking probability instead of a sharp velocity threshold. We developed a model to explain the physical processes involved in dust-aggregate sticking, derived dynamical material properties of the dust aggregates from the results of the collisions, and deduced the velocity below which dust aggregates always stick. For millimeter-sized porous dust aggregates this velocity is 8 x 10-5 m s-1.

## 2011 Geretshauser

13 October , Speith, Kley

### Collisions of inhomogeneous pre-planetesimals

#### Modelling (preplanetesimals (inhomogeneous, fluffy, porous, dust aggregates), subsequent collisions), inhomogeneity model based on: density distribution of dust aggregates, typical size of aggregates (cm), smoothed particle hydrodynamics code, porosity model, results: inhomogeneous preplanetesimals more likely destroyed than homogeneous aggregates, size of fragments decreases with increasing inhomogeneity => possible obstacle to collisional growth (active history = weaker aggregate)

*Context*. In the framework of the coagulation scenario, kilometre-sized planetesimals form by subsequent collisions of preplanetesimals of sizes from centimetre to hundreds of metres. Pre-planetesimals are fluffy, porous dust aggregates, which are inhomogeneous owing to their collisional history. Planetesimal growth can be prevented by catastrophic disruption in pre-planetesimal collisions above the destruction velocity threshold.

*Aims*. We assess whether the inhomogeneity created by subsequent collisions has a significant influence on the stability of preplanetesimal material to withstand catastrophic disruption. We wish to develop a model that is explicitly able to resolve any inhomogeneous structures. The input parameters of this model must be easily accessible from laboratory measurements.

*Methods*. We develop an inhomogeneity model based on the density distribution of dust aggregates, which is assumed to be a Gaussian distribution with a well-defined standard deviation. As a second input parameter, we consider the typical size of an inhomogeneous clump. For the simulation of the dust aggregates, we utilise a smoothed particle hydrodynamics (SPH) code with extensions for modelling porous solid bodies. The porosity model was previously calibrated for the simulation of SiO2 dust, which commonly serves as an analogue for pre-planetesimal material. The inhomogeneity is imposed as an initial condition on the SPH particle distribution. We carry out collisions of centimetre-sized dust aggregates of intermediate porosity. We vary the standard deviation of the inhomogeneous distribution at fixed typical clump size. The collision outcome is categorised according to the four-population model.

*Results*. We show that inhomogeneous pre-planetesimals are more prone to destruction than homogeneous aggregates. Even slight inhomogeneities can lower the threshold for catastrophic disruption. For a fixed collision velocity, the sizes of the fragments decrease with increasing inhomogeneity.

*Conclusions*. Pre-planetesimals with an active collisional history tend to be weaker. This is a possible obstacle to collisional growth and needs to be taken into account in future studies of the coagulation scenario.

## 2011 Teiser

29 July , Küpper, Wurm

### Impact angle influence in high velocity dust collisions during planetesimal formation

#### dust aggregate(from m particles) collisions, small (1-5 mm) on target, 20 m/s, 0° - 45°, supports sweep-up planetesimal formation

We have examined the influence of impact angle in collisions between small dust aggregates and larger dust targets through laboratory experiments. Targets consisted of m-sized quartz dust and had a porosity of about 67%; the projectiles, between 1 and 5 mm in diameter, were slightly more compact (64% porosity). The collision velocity was centered at 20 m/s and impact angles range from 0° to 45°. At a given impact angle, the target gained mass for projectiles smaller than a threshold size, which decreases with increasing angle from about 3 mm to 1 mm. The fact that growth is possible up to the largest angles studied supports the idea of planetesimal formation by sweep-up of small dust aggregates.

## 2011 Beitz

29 April , Güttler, Blum, Meisner, Teiser, Wurm

### LOW-VELOCITY COLLISIONS OF CENTIMETER-SIZED DUST AGGREGATES

#### lab dust (cm – decimeter size) collisions, setup 1 - microgravity (8x10-3 – 2 m/s), setup 2 - mass transfer (fragmentation velocity 20 cm/s), critical energy for disruptive collisions Q\* two orders of magnitude lower than in literature, accretion efficiency (few %) depends on impact velocity & porosity

Collisions between centimeter- and decimeter-sized dusty bodies are important in understanding the mechanisms leading to the formation of planetesimals. We performed laboratory experiments to study the collisional behavior of dust aggregates in this size range at velocities below and around the fragmentation threshold. We developed two independent experimental setups with the same goal: to study the effects of bouncing, fragmentation, and mass transfer in free particle–particle collisions. The first setup is an evacuated drop tower with a free-fall height of 1.5 m, providing us with 0.56 s of microgravity time, so that we observed collisions with velocities between 8 mm s−1 and 2 m s−1. The second setup is designed to study the effect of partial fragmentation (when only one of the two aggregates is destroyed) and mass transfer in more detail. It allows for the measurement of the accretion efficiency because the samples are safely recovered after the encounter. At very low velocities, we found that bouncing was as expected, while the fragmentation velocity of 20 cm s−1 was significantly lower than expected. We present the critical energy for disruptive collisions Q⋆, which were at least two orders of magnitude lower than previous experiments in the literature. In the wide range between bouncing and disruptive collisions, only one of the samples fragmented in the encounter, while the other gained mass. The accretion efficiency on the order of a few percentage points of the particle’s mass depends on the impact velocity and the sample porosity. Our results will have consequences for dust evolution models in protoplanetary disks as well as for the strength of large, porous planetesimal bodies.

## 2011 Schräpler

7 April , Blum

### The physics of protoplanetesimal dust agglomerates.

### VI. Erosion of large aggregates as a source of micrometer-sized particles

#### Collision experiments (erosion of macroscopic dust agglomerates (μm-sized silica spheres) via impact of μm-sized particles), initial phase (impact erodes up to 10 particles), then compression by impacts (partial passivation of agglomerate) => no erosion for v <̰ 30 m/s, erosion reduced by 1 order of magnitude for v >̰ 30 m/s, confirmed by numerical model, built analytical disk model => erosion is strong source of μm-sized particles in pp disk, explains observations (Furlan et.al)

Observed protoplanetary disks consist of a large amount of micrometer-sized particles. Dullemond & Dominik pointed out for the first time the difficulty in explaining the strong mid-infrared excess of classical T Tauri stars without any dust-retention mechanisms. Because high relative velocities in between micrometer-sized and macroscopic particles exist in protoplanetary disks, we present experimental results on the erosion of macroscopic agglomerates consisting of micrometer-sized spherical particles via the impact of micrometer-sized particles. We find that after an initial phase, in which an impacting particle erodes up to 10 particles of an agglomerate, the impacting particles compress the agglomerate’s surface, which partly passivates the agglomerates against erosion. Due to this effect, the erosion halts for impact velocities up to ≈ 30m/s within our error bars. For higher velocities, the erosion is reduced by an order of magnitude. This outcome is explained and confirmed by a numerical model. In a next step, we build an analytical disk model and implement the experimentally found erosive effect. The model shows that erosion is a strong source of micrometer-sized particles in a protoplanetary disk. Finally, we use the stationary solution of this model to explain the amount of micrometer-sized particles in the observational infrared data of Furlan et al.

## 2010 Blum

### Dust growth in protoplanetary disks – a comprehensive experimental/theoretical approach

#### review (lab & modelling), collisional sticking alone not enough, streaming and gravitational instability best candidates for planetesimal growth in protoplanetary disk

More than a decade of dedicated experimental work on the collisional physics of protoplanetary dust has brought us to a point at which the growth of dust aggregates can – for the first time – be self-consistently and reliably modeled. In this article, the emergent collision model for protoplanetary dust aggregates (Güttler et al., 2010) as well as the numerical model for the evolution of dust aggregates in protoplanetary disks (Zsom et al., 2010) are reviewed. It turns out that, after a brief period of rapid collisional growth of fluffy dust aggregates to sizes of a few centimeters, the protoplanetary dust particles are subject to bouncing collisions, in which their porosity is considerably decreased. The model results also show that low-velocity fragmentation can reduce the final mass of the dust aggregates but that it does not trigger a new growth mode as discussed previously. According to the current stage of our model, the direct formation of kilometer-sized planetesimals by collisional sticking seems impossible so that collective effects, such as the streaming instability and the gravitational instability in dust-enhanced regions of the protoplanetary disk, are the best candidates for the processes leading to planetesimals.

## 2010 Kothe

21 September , Güttler, Blum

### The physics of protoplanetesimal dust agglomerates.

### V. Multiple impacts of dusty agglomerates at velocities above the fragmentation threshold

#### Collision experiments on mass transfer in shattering collisions (lab + drop tower, agglomerates of μm-sized silica spheres as projectile + target (volume filling factors: 0.15 & 0.45 respectively), velocities 1.5 – 6 m/s), result: linear increase of accretion efficiency with impact v (12 – 21 % of projectile mass), growth of conical structure on target after < 100 impacts (volume filling factor: 0.15 – 0.4, increasing with increasing impact v)

In recent years, a number of new experiments have advanced our knowledge on the early growth phases of protoplanetary dust aggregates. Some of these experiments have shown that collisions between porous and compacted agglomerates at velocities above the fragmentation threshold velocity can lead to growth of the compact body, when the porous collision partner fragments upon impact and transfers mass to the compact agglomerate. To obtain a deeper understanding of this potentially important growth process, we performed laboratory and drop tower experiments to study multiple impacts of small, highly porous dust-aggregate projectiles onto sintered dust targets. The projectile and target consisted of 1.5 μm monodisperse, spherical SiO2 monomers with volume filling factors of 0.15 ± 0.01 and 0.45 ± 0.05, respectively. The fragile projectiles were accelerated by a solenoid magnet and combined with a projectile magazine with which 25 impacts onto the same spot on the target could be performed in vacuum. We measured the mass-accretion efficiency and the volume filling factor for different impact velocities between 1.5 and 6.0 m/s. The experiments at the lowest impact speeds were performed in the Bremen drop tower under microgravity conditions to allow partial mass transfer also for the lowest adhesion case. Within this velocity range, we found a linear increase of the accretion efficiency with increasing velocity. In the laboratory experiments, the accretion efficiency increases from 0.12 to 0.21 in units of the projectile mass. The recorded images of the impacts showed that the mass transfer from the projectile to the target leads to the growth of a conical structure on the target after less than 100 impacts. From the images, we also measured the volume filling factors of the grown structures, which ranged from 0.15 (uncompacted) to 0.40 (significantly compacted) with increasing impact speed. The velocity dependency of the mass-transfer efficiency and the packing density of the resulting aggregates augment our knowledge of the aggregate growth in protoplanetary disks and should be taken into account for future models of protoplanetary dust growth.

## 2010 Zsom

4 January , Ormel, Güttler, Blum, Dullemond

### The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals?

### II. Introducing the bouncing barrier

#### collision model based on lab experiments (dust aggregates), investigation of upper size limits for coagulation in protoplanetary disks, dust is modelled as spheres with porous and compact phases (continuous transition), include Brownian motion/radial drift/turbulence, 1 AU, midplane, different gas densities, catastrophic fragmentation very rare, quasi-steady states in distribution function by bouncing, turbulence has non-linear influence, aerodynamic size sorting of particles

*Context.* The sticking of micron-sized dust particles caused by surface forces within circumstellar disks is the first stage in the production of asteroids and planets. The key components describing this process are the relative velocity between the dust particles in this environment and the complex physics of dust aggregate collisions.

*Aims.* We present the results of a collision model based on laboratory experiments of these aggregates. We investigate the maximum aggregate size and mass that can be reached by coagulation in protoplanetary disks.

*Methods.* We use the results of laboratory experiments to establish the collision model previously published by Güttler et al. The collision model is based on the assumptions that we model the aggregates as spheres with compact and porous “phases” and that there is a continuous transition between these two. We apply this collision model to the Monte Carlo method developed previously by Zsom & Dullemond and include Brownian motion, radial drift, and turbulence as contributors of relative velocity between dust particles.

*Results.* We model the growth of dust aggregates at 1 AU in the midplane for three different gas densities. We find that the evolution of the dust does not follow the previously assumed growth-fragmentation cycles. Catastrophic fragmentation hardly occurs in the three disk models. Furthermore, we see long-lived, quasi-steady states in the distribution function of the aggregates caused by bouncing. We explore how the mass and the porosity depend on both the turbulence parameter and the critical mass ratio of dust particles. Upon varying the turbulence parameter, the system behaves in a non-linear way, and we find that the critical mass ratio has a strong effect on the particle sizes and masses. Particles reach Stokes numbers of roughly 10−4 during the simulations.

*Conclusions.* The particle growth is stopped by bouncing rather than fragmentation in these models. The final Stokes number of the aggregates is rather insensitive to the variations in the gas density and the strength of turbulence. The maximum mass of the particles is limited to ≈1 g (chondrule-sized particles). Planetesimal formation can proceed by the means of the turbulent concentration of these aerodynamically size-sorted, chondrule-sized particles.

## 2010 Güttler

16 November 2009 , Blum, Zsom, Ormel, Dullemond

### The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals?

### I. Mapping the zoo of laboratory collision experiments

#### complete collision model for protoplanetary dust, based on old literature/new experiments/simple physical model, four different kinds of sticking/two kinds of bouncing/three kinds of fragmentation, similar-sized/different-sized bodies

*Context.* The growth processes from protoplanetary dust to planetesimals are not fully understood. Laboratory experiments and theoretical models have shown that collisions among the dust aggregates can lead to sticking, bouncing, and fragmentation. However, no systematic study on the collisional outcome of protoplanetary dust has been performed so far so that a physical model of the dust evolution in protoplanetary disks is still missing.

*Aims.* We intend to map the parameter space for the collisional interaction of arbitrarily porous dust aggregates. This parameter space encompasses the dust-aggregate masses, their porosities and the collision velocity. With such a complete mapping of the collisional outcomes of protoplanetary dust aggregates, it will be possible to follow the collisional evolution of dust in a protoplanetary disk environment.

*Methods.* We use literature data, perform own laboratory experiments, and apply simple physical models to get a complete picture of the collisional interaction of protoplanetary dust aggregates.

*Results.* In our study, we found four different kinds of sticking, two kinds of bouncing, and three kinds of fragmentation as possible outcomes in collisions among protoplanetary dust aggregates. Our best collision model distinguishes between porous and compact dust. We also differentiate between collisions among similar-sized and different-sized bodies. All in all, eight combinations of porosity and mass ratio can be discerned. For each of these cases, we present a complete collision model for dust-aggregate masses between 10−12 and 102 g and collision velocities in the range 10−4 … 104 cm s−1 for arbitrary porosities. This model comprises the collisional outcome, the mass(es) of the resulting aggregate(s) and their porosities.

*Conclusions.* We present the first complete collision model for protoplanetary dust. This collision model can be used for the determination of the dust-growth rate in protoplanetary disks.

## 2009 Teiser

29 June , Wurm

### Decimetre dust aggregates in protoplanetary discs

#### collision experiments, SiO2 (m) aggregates (sub-mm) with dust targets, 7.7 m/s (expected for decimetre size bodies in protoplanetary disks), part of projectile sticks directly, small parts aggregate later by gravity, crust growing (several cm thick), initially very porous (31 % filing), compacting in consecutive collisions, average COR 0.29

The growth of planetesimals is an essential step in planet formation. Decimetre-size dust agglomerates mark a transition point in this growth process. In laboratory experiments we simulated the formation, evolution, and properties of decimetre-scale dusty bodies in protoplanetary discs. Small sub-mm size dust aggregates consisting of micron-size SiO2 particles randomly interacted with dust targets of varying initial conditions in a continuous sequence of independent collisions. Impact velocities were 7.7 m/s on average and in the range expected for collisions with decimetre bodies in protoplanetary discs. The targets all evolved by forming dust *crusts* with up to several cm thickness and a unique filling factor of 31% ± 3%. A part of the projectiles sticks directly. In addition, some projectile fragments slowly return to the target by gravity. All initially porous parts of the surface, i.e. built from the slowly returning fragments, are compacted and firmly attached to the underlying dust layers by the subsequent impacts. Growth is possible at impact angles from 0◦ (central collision) to 70◦. No growth occurs at steeper dust surfaces. We measured the velocity, angle, and size distribution of collision fragments. The average restitution coefficient is 3.8% or 0.29 m/s ejection velocity. Ejecta sizes are comparable to the projectile sizes. The high filling factor is close to the most compact configuration of dust aggregates by local compression (∼33%). This implies that the history of the surface formation and target growth is completely erased. In view of this, the filling factor of 31% seems to be a universal value in the collision experiments of all self-consistently evolving targets at the given impact velocities. We suggest that decimetre and probably larger bodies can simply be characterised by one single filling factor. While gravity dominates re-accretion in the experiments, small fragments will be re-accreted as well in protoplanetary discs by gas drag at the given low ejection velocities. The accretion efficiency in planetesimal growth is model dependent. However, a small fraction of small particles re-accreted by gas flow or direct sticking readily allows growth of dusty bodies in protoplanetary discs in the decimetre range.

## 2009 Mutschke

16 June , Min, Tamanai

### Laboratory-based grain-shape models for simulating dust infrared spectra

#### Lab and calculated dust extinction spectra often not in good agreement, modelling with distribution of form factors (DFF) to match lab results -> later grain shapes can be derived from model fits independently

*Context.* Analysis of thermal dust emission spectra for dust mineralogy and physical grain properties depends on comparison spectra, which are either laboratory-measured infrared extinction spectra or calculated extinction cross sections based on certain grain models. Often, the agreement between these two kinds of spectra, if available, is not yet satisfactory because of the strong influence of the grain morphology on the spectra.

*Aims.* We investigate the ability of the statistical light-scattering model with a distribution of form factors (DFF) to reproduce measured infrared dust extinction spectra for particles that are small compared to the wavelength, i.e. in the size range of 1 μm and smaller.

*Methods.* We take advantage of new experimental spectra measured for free particles dispersed in air with accompanying information on the grain morphology. For the calculations, we used DFFs that were derived for aggregates of spherical grains, as well as for compact grain shapes corresponding to Gaussian random spheres. In addition we used a fitting algorithm to obtain the best-fit DFFs for the various laboratory samples. In this way we can independently derive information on the shape of the grains from their infrared spectra.

*Results.* With the DFF model, we achieve an adequate fit of the experimental IR spectra. The differences in the IR band profiles between the spectra of particulates with different grain shapes are simply reflected by different DFFs. Irregular particle shapes require a DFF similar to that of a Gaussian Random Sphere with σ = 0.3, whereas roundish grain shapes are best fitted with that of a fractal aggregate of *D*f = 2.4–1.8. The fitted DFFs generally reproduce the measured spectral shapes quite well. For anisotropic materials, different DFFs are needed for the different crystallographic axes. The implications of this finding are discussed.

*Conclusions.* The use of this model could be a step forward toward more realistic comparison data in infrared spectral analysis of thermal dust emission spectra, provided that these spectra are dominated by emission from submicron grains.

## 2009 Weidling

24 February , Güttler, Blum, Brauer

### The physics of protoplanetesimal dust agglomerates

### III. Compaction in multiple collisions

#### Collision experiments (highly porous (volume filling factor 0.15) dust aggregates (of spherical 1.5 μm grains) with solid plate, 0.2 m/s, multiple (≤ 2600) collisions with same aggregate), results: volume filling factor increased by a factor of > 2, fragmentation in few cases (not expected, as threshold is usually higher v)

To study the evolution of protoplanetary dust aggregates, we performed experiments with up to 2600 collisions between single, highly porous dust aggregates and a solid plate. The dust aggregates consisted of spherical SiO2 grains with 1.5 μm diameter and had an initial volume filling factor (the volume fraction of material) of φ0 = 0.15. The aggregates were put onto a vibrating baseplate and, thus, performed multiple collisions with the plate at a mean velocity of 0.2 m/s. The dust aggregates were observed by a high-speed camera to measure their size which apparently decreased over time as a measure for their compaction. After 1000 collisions the volume filling factor was increased by a factor of 2, while after ∼2000 collisions it converged to an equilibrium of φ ≈ 0.36. In few experiments the aggregate fragmented, although the collision velocity was well below the canonical fragmentation threshold of ∼1 m/s. The compaction of the aggregate has an influence on the surface-to-mass ratio and thereby the dynamic behavior and relative velocities of dust aggregates in the protoplanetary nebula. Moreover, macroscopic material parameters, namely, the tensile strength, shear strength, and compressive strength, are altered by the compaction of the aggregates, which has an influence on their further collisional behavior. The occurrence of fragmentation requires a reassessment of the fragmentation threshold velocity.

## 2009 Teiser

21 November 2008 , Wurm

### High-velocity dust collisions: forming planetesimals in a fragmentation cascade with final accretion

#### lab dust collisions, up to 56.5 m/s, cm – decimetre size targets, sub-mm – cm size projectiles, varying shape, projectiles > 1 mm -> slight erosion of target, decimetre targets don’t break up, small ejecta produced, projectiles < 1 mm accrete (even at high velocities

In laboratory experiments we determine the mass gain and loss in central collisions between centimetre- to decimetre-size SiO2 dust targets and submillimetre- to centimetre-size SiO2 dust projectiles of varying mass, size, shape and at different collision velocities up to ∼56.5 m s−1. ­Dust projectiles much larger than 1 mm lead to a small amount of erosion of the target but decimetre targets do not break up. Collisions produce ejecta, which are smaller than the incoming projectile. Projectiles smaller than 1 mm are accreted by a target even at the highest collision velocities. This implies that net accretion of decimetre and larger bodies is possible. Independent of the original size of a considered projectile, after several collisions, all fragments will be of submillimetre size which might then be (re)accreted in the next collision with a larger body. The experimental data suggest that collisional growth through fragmentation and reaccretion is a viable mechanism to form planetesimals.

## 2008 Wada

14 January , Tanaka, Suyama, Kimura, Yamamoto

### NUMERICAL SIMULATION OF DUST AGGREGATE COLLISIONS.

### II. COMPRESSION AND DISRUPTION OF THREE-DIMENSIONAL AGGREGATES IN HEAD-ON COLLISIONS

#### Numerical simulations (dust aggregate collisions, 3D head-on)

We study collisions between dust aggregates to construct a model of their structural evolution in protoplanetary disks. We carry out three-dimensional simulations of aggregate collisions and examine their compression and disruption processes following our previous two-dimensional simulations. We take clusters of ballistic cluster-cluster aggregation (BCCA) formed by a hit-and-stick process as initial structures and study their head-on collisions with the use of realistic binding forces. Our numerical results indicate that the energy criteria for compression and disruption of BCCA clusters are consistent with previous two-dimensional simulations. For aggregate compression at a collision, we succeed in obtaining a scaling law in which the gyration radius of the resultant aggregate is proportional to , where *E*imp is the impact energy. Furthermore, we derive an ‘‘equation of state’’ of aggregates which reproduces the scaling law for compression. The equation of state is useful for describing the density evolution of dust aggregates during their growth.

## 2007 Wada

13 February , Tanaka, Suyama, Kimura, Yamamoto

### NUMERICAL SIMULATION OF DUST AGGREGATE COLLISIONS.

### I. COMPRESSION AND DISRUPTION OF TWO-DIMENSIONAL AGGREGATES

#### Numerical simulations (dust aggregate collisions, 2D head-on), compression & disruption, degree of maximum compression determined by ratio of rolling energy to breaking energy, ice aggregates become more compact than quartz aggregates (same impact conditions), aggregates harder to disrupt with increasing number of particles

We carry out numerical simulations of dust aggregate collisions to study the compression and disruption processes of aggregates in their growth. To compare with the pioneering studies of Dominik & Tielens, we focus on two-dimensional head-on collisions, in which we obtain similar results for compression and disruption to theirs. In addition to the similarities, we examine the dependence of the collisional outcomes on the aggregate size and the parameters relevant to the particle interaction in detail by treating large aggregates that consist of up to 2000 particles. Compression of aggregates by collisions reduces the radius of gyration and increases the number of contacts between the constituent particles. Our results show that the changes in the gyration radius and the number of contacts after impact depend on the impact energy and that the dependence is scaled by the energy necessary to roll all contacts. We provide empirical formulae for the changes in the gyration radius and the number of contacts. Furthermore, we find that the degree of maximum compression is determined by the ratio of rolling energy to breaking energy. This indicates that ice aggregates become more compact than quartz aggregates in the same impact conditions. Any aggregates are catastrophically disrupted when the impact energy exceeds approximately 10 times the energy necessary to break all contacts. Our results, however, suggest that it becomes harder to disrupt the aggregates with an increasing number of particles.

## 2007 Ormel

27 September 2006 , Spaans, Tielens

### Dust coagulation in protoplanetary disks: porosity matters

#### Modelling (coupling between dust and gas depends on porosity, aim: quantify influence in turbulent disk, three regimes: hit-and-stick, compaction, fragmentation), results: three stages (initially growth driven by Brownian motion -> high porosity, then turbulent higher velocities -> compaction, then settling out to the mid-plane, aggregates can grow to (porous) sizes of ≈ 10 cm in a few thousand years, before raining out to mid-plane

*Context*. Sticking of colliding dust particles through van der Waals forces is the first stage in the grain growth process in protoplanetary disks, eventually leading to the formation of comets, asteroids and planets. A key aspect of the collisional evolution is the coupling between dust and gas motions, which depends on the internal structure (porosity) of aggregates.

*Aims*. To quantify the importance of the internal structure on the collisional evolution of particles, and to create a new coagulation model to investigate the difference between porous and compact coagulation in the context of a turbulent protoplanetary disk.

*Methods*. We have developed simple prescriptions for the collisional evolution of porosity of grain-aggregates in grain-grain collisions. Three regimes can then be distinguished: “hit-and-stick” at low velocities, with an increase in porosity; compaction at intermediate velocities, with a decrease of porosity; and fragmentation at high velocities. This study has been restricted to physical regimes where fragmentation is unimportant. The temporal evolution has been followed using a Monte Carlo coagulation code.

*Results*. This collision model is applied to the conditions of the (gas dominated) protoplanetary disk, with an αT parameter characterising the turbulent viscosity. We can discern three different stages in the particle growth process. Initially, growth is driven by Brownian motion and the relatively low velocities involved lead to a rapid increase in porosity of the growing aggregate. The subsequent second stage is characterised by much higher, turbulent driven velocities and the particles compact. As they compact, their mass-to-surface area increases and eventually they enter the third stage, the settling out to the mid-plane. We find that when compared to standard, compact models of coagulation, porous growth delays the onset of settling, because the surface area-to-mass ratio is higher, a consequence of the build-up of porosity during the initial stages. As a result, particles grow orders of magnitudes larger in mass before they rain-out to the mid-plane. Depending on the precise value of αT and on the position in the nebula, aggregates can grow to (porous) sizes of ∼10 cm in a few thousand years. We also find that collisional energies are higher than in the limited PCA/CCA fractal models, thereby allowing aggregates to restructure. It is concluded that the microphysics of collisions plays a key role in the growth process.

## 2006 Blum

17 October

### Dust agglomeration

#### Review (physical interactions that lead to sticking in gaseous environments, morphologies of resulting dust aggregates, modelling (temporal evolution + mass distribution of aggregates))

Dust agglomeration plays an important role in astrophysics and atmospheric sciences as well as in industrial processes. This article reviews the current knowledge of the physical interactions that lead to particle sticking in gaseous environments as well as the morphologies of the resulting dust aggregates. With this basic knowledge of dust–dust interactions, the development of ensembles of interacting dust particles can be treated using Smoluchowski’s equation. Considering analytical solutions and simplified physical conditions, the temporal evolution and the mass distribution functions of dust aggregates are discussed. Based on this, general dust aggregation phenomena can be modelled and introduced into more complex scenarios.

## 2005 Wurm

### Growth of planetesimals by impacts at ~25 m/s

#### dust (mm-size to cm-size target), v ≤ 25 m/s, net growth at high speed collisions, fast ejecta 500 m, 40 % of impact velocity)

We study central collisions between millimeter-sized dust projectiles and centimeter-sized dust targets in impact experiments. Target and projectile are dust aggregates consisting of micrometer-sized SiO2 particles. Collision velocities range up to 25 m/s. The general outcome of a collision strongly depends on the impact velocity. For collisions below 13 m/s rebound and a small degree of fragmentation occur. However, at higher collision velocities up to 25 m/s approximately 50% of the mass of the projectile rigidly sticks to the target after the collision. Thus, net growth of a body is possible in high speed collisions. This supports the idea that planetesimal formation via collisional growth is a viable mechanism at higher impact velocities. Within our set of parameters the experiments even suggest that higher impact velocities might be preferable for growth in collisions between dusty bodies. For the highest impact velocities most of the ejecta is within small dust aggregates about 500 μm in size. In detail the size distribution of ejected dust aggregates is flat for very small particles smaller than 500 μm and follows a power law for larger ejected dust aggregates with a power of −5.6 ± 0.2. There is a sharp upper cut-off at about 1 mm in size with only a few particles being slightly larger. The ejection angle is smaller than 3◦ with respect to the target surface. These fast ejecta move with 40 ± 10% of the impact velocity.

## 2004 Krause

9 July , Blum

### Growth and Form of Planetary Seedlings: Results from a Sounding Rocket Microgravity Aggregation Experiment

#### Collision experiment (microgravity (sounding rocket), Brownian motion-induced collisions), results: dust agglomerates have fractal dimensions as low as 1.4, temporal evolution of mean agglomerate mass described by power law, collision cross section = geometrical cross section, mass-distribution function

In a second microgravity experiment on the formation of dust agglomerates by Brownian motion-induced collisions we find that the agglomerates have fractal dimensions as low as 1.4. Because of much better data, we are now able to derive the diffusion constant of the agglomerates as a function of mass, to show that a power law with an exponent of 1.7 describes the temporal evolution of the mean agglomerate mass very well and to prove that the collision cross section is proportional to the geometrical cross section. In addition to that we derived the universal mass-distribution function of the agglomerates.

## 2004 Gail

29 August 2003

### Radial mixing in protoplanetary accretion disks

### IV. Metamorphosis of the silicate dust complex

#### Modelling (evolution of main dust components, chemical composition, Mg-Fe-silicates, Mg-silicates & Fe, advection-diffusion, radial mixing), resulting mineral mixtures are in rough agreement with matrix material of meteorites/cometary nuclei

The outer regions of protoplanetary accretion discs are formed by material from the parent molecular cloud of the freshly forming stars. The interstellar dust in this material is a mixture of species which does not correspond to any kind of chemical equilibrium state between the solid and gaseous phases. Mass accretion carries this material into the warm inner disc zones where chemical and physical processes are activated which convert the non-equilibrium solid-gas mixture into a chemical equilibrium mixture. Part of the equilibrated material is then mixed outwards by turbulent diffusion and large-scale circulation currents. This work specifically considers the evolution of the main dust components, viz. from the interstellar mixture of amorphous Mg-Fe-silicates, into a chemical equilibrium mixture of crystalline Mg-silicates, and iron. The basic set of equations for calculating the evolution of a mixture of silicates and iron is derived. Model calculations based on stationary, one-zone α-discs are combined with the advection-diffusion-reaction equations for the dust evolution to study the interstellar to equilibrium dust conversion and the radial mixing of equilibrated dust into the outer disc regions. This determines the mixture of the main dust components which form the mineral inventory of planetesimals. It is found that the results of the model calculation for the resulting mineral mixture are in rough agreement with the composition of matrix material of primitive meteorites and dust in cometary nuclei.

## 2002 Blum

February , Wurm, Poppe, Kempf, Kozasa

### First results from the cosmic dust aggregation experiment codag

#### Collision experiments (microgravity (sounding rocket, duration: several minutes), Brownian motion-induced coagulation process of μm-sized dust), result: subsequent collisions form fractal dust aggregates

The Cosmic Dust Aggregation Experiment (CODAG), an experimental simulation of the onset of planet formation, was successfully flown on STS-95 (October/November 1998) and on Maser 8 (May 1999). The main objective of the CODAG experiment was a direct observation of the Brownian motion-induced coagulation process of micron-sized dust particles. To overcome rapid sedimentation of the dust grains in the rarefied gas atmosphere, experiments were conducted in a long-duration microgravity environment. In the experiment, we observed that within several minutes the initially deagglomerated dust grains formed fractal dust aggregates due to their thermal motion and subsequent mutual collisions. The results from this experiment are the first experimental proof that the concept of pre-planetary dust coagulation is correct.

## 2000 Poppe

15 November 1999 , Blum, Henning

### Experiments on collisional grain charging of micron-sized preplanetary dust

#### Collision experiments on collisional charging (μm-sized grains impacting target surface (non-conducting)), reason: former experiments (particles returning to target after rebound, particle deposition on targets in presence of conducting materials), results: collisional charging stronger than anticipated, needs to be considered (preplanetary dust aggregation, lightning formation in solar nebula, charged grain coupling to magnetic fields)

Collisions between micron-sized grains and larger objects with velocities up to several 10 m/s are believed to be an important physical process in the solar nebula with respect to the preplanetary dust aggregation. Former collision experiments demonstrated that grain-target collisions of micron-sized particles were marked by obvious electrostatic effects. Among those were the observation of particles which, after mechanical rebound, returned to the target and finally stuck, and of particle deposition on targets influenced by the presence of conducting materials. Therefore, it is clear that the dust aggregation process cannot adequately be described without investigating collisional grain charging experimentally. We present experiments on the collisional grain charging of micron-sized grains impacting target surfaces which, in contrast to former work, consist both of nonconducting material and the experiments involving smaller particles than before. Collisional grain charging is stronger than previously discussed with respect to preplanetary grains and should be considered concerning the preplanetary dust aggregation, the formation of lightning in the solar nebula, and a coupling of charged grains to magnetic fields.

## 2000 Poppe

15 November 1999 , Blum, Henning

### ANALOGOUS EXPERIMENTS ON THE STICKINESS OF MICRON-SIZED PREPLANETARY DUST

#### different dust materials (silica, diamond, enstatite, silicon carbide), stickier than theoretically predicted, stickiness depends more on size/shape/roughness than on material

In the early solar nebula, the formation of planetesimals and cometesimals is believed to be due to inelastic collisions of initially micron-sized grains. The collisions are caused by relative velocities due to size-dependent interactions with the surrounding dilute gas. The grain growth process is determined by the velocity-dependent sticking efficiency upon collisions. Therefore, we performed experiments with eight samples of micron-sized particles consisting of monodisperse silica spheres, of irregularly shaped diamond, enstatite, and silicon carbide grains, and of silicon carbide whiskers. We determined the sticking probability and the energy loss upon bouncing collisions by studying individual grain-target collisions in vacuum. We found a sticking probability higher than predicted by previous theoretical work. Grain size, roughness, and primarily grain shape, i.e., the difference of spherical versus irregular grain shape, is important for the collisional behavior, whereas the material properties are rather unimportant. Our results indicate that the preplanetary dust aggregation is more effective than previously thought.

## 2000 Blum

8 March 1999 , Wurm

### Experiments on Sticking, Restructuring, and Fragmentation of Preplanetary Dust Aggregates

#### Collision experiments (lab & microgravity (drop tower), small dust aggregates (of μm-sized particles) onto solid targets), results: slow impacts in lab: formation of fluffy dust layer (gravity induced compaction in that), fast impacts in microgravity (v > few m/s): disruption of agglomerates, slower impacts in microgravity: sticking and removal from target, slow impacts in microgravity: sticking probability = 1, formation of compact dust layer, slowest impacts in microgravity: no compaction -> growth of very porous dust layer. Computer simulations based on rolling friction force and break-up energy => planet formation: dust aggregates below a few cm in diameter not expected to be subject to impact compaction

We performed laboratory as well as microgravity experiments in which we studied the impact of small fractal aggregates consisting of micrometer-sized dust particles onto solid targets at various velocities. Slow bombardment of the target in the laboratory results in the formation of a fluffy dust layer in which gravity-induced compaction is observed. In order to reduce the gravitational aggregate restructuring and, hence, to investigate the collisional behavior of fluffy dust aggregates, we performed additional experiments in the microgravity environment of a drop tower. We observe that the agglomerates are disrupted as long as the impact velocities are above a few meters per second. For slightly lower collision velocities, both sticking to and removal from the target are detected. At even lower velocities, the impinging dust agglomerates are captured by the target with a sticking probability of unity, and a compact dust layer forms. When the impact energies are no longer sufficiently large to allow for agglomerate restructuring, the internal structures of the impacting aggregates are preserved, and we observe the growth of a very porous dust layer. The results of our experiments are in qualitative, but not in quantitative agreement with theoretical predictions. Full quantitative accordance between computer simulations and experiments can be reached when the recently measured values for the rolling friction force Froll=1.2×10−9 N and for the break-up energy Ebr=1.3×10−15 J (valid for 1.9-μm-diameter SiO2 spheres) are used. Our experimental results suggest that aggregate restructuring in the solar nebula, and hence, the gradual increase of the fractal dimensionality of the dust agglomerates, becomes an important process when the aggregate diameters exceed a few centimeters. Dust aggregates below that size are not expected to be subjected to impact compaction.

## 1999 Heim

18 October , Blum, Preuss, Butt

### Adhesion and Friction Forces between Spherical Micrometer-Sized Particles

#### Characterization experiments (adhesion, rolling friction force, silica microspheres, 0.5 – 2.5 μm), result: rolling friction force ≈ 100 x lower than adhesion

An experimental setup, based on the principles of atomic force microscopy (AFM), was used to measure directly the adhesion and rolling-friction forces between individual silica microspheres of radii between 0.5 and 2.5 μm. It showed that the linear dependence of the pull-off force on the particle radius is still valid for micron-sized particles. Rolling-friction forces between silica microspheres were measured for the first time by combining AFM methods and optical microscopy: They are ≈ 100 times lower than the corresponding adhesion forces.

## 1993 Blum

10 May , Münch

### Experimental Investigations on Aggregate-Aggregate Collisions in the Early Solar Nebula

#### Collision experiments (vacuum, 2 mm-sized dust aggregates (ZrSiO4 ≤ 1 μm, 74 % porosity / SiO2 ≈ 12 nm, 97 % porosity), 0.15 – 4 m/s, central to grazing collisions, mass ratios of collision partners 1:1 & 1:66), results: no coagulation (sticking), low v: bouncing, high v: transition to fragmentation (1:1 experiment: transition @ v ≈ 1m/s (ZrSiO4), @ ≈ 4 m/s (SiO2) / 1:66 experiment: transition unclear), fragmentation of 1:1 ZrSiO4: abundance of small fragments increases with increasing v and decreasing impact parameter, power law mass distribution of fragments -> fragmentation model (constant free surface energy per unit surface area of fragments, impact parameter-dependent efficiency for transition of kinetic collision energy into free surface energy of fragments) -> predicts complete disintegration of the ZrSiO4 aggregates for v ≥ 50 m/s, prediction based on van der Waals-bonded constituents: ≈ 3 m/s, typical velocities for the preplanetary nebula -> catastrophic fragmentations could be frequent if aggregates formed by weak surface forces.

Low-velocity aggregate-aggregate collisions play an important role for the development of aggregate sizes during the first stages of accumulation of solid bodies in the preplanetary nebula. To study such collisions, an experimental setup was developed where two millimeter-sized dust aggregates collide in vacuum with relative velocities between ∼0.15 and ∼4 m/s. The impact parameters of the collisions are arbitrary so that central collisions as well as grazing collisions can be investigated. Two types of aggregates were used, (1) ZrSiO4 with constituent particle sizes ≤1 μm and 74% porosity and (2) Aerosil 200 (SiO2) with constituent particle sizes ∼12 nm and 97% porosity. The collision experiments were carried out in five narrow velocity windows in the above velocity regime for equal-sized aggregates (ZrSiO4 (I), Aerosil 200) as well as for aggregates with a mean mass ratio of ∼66 (ZrSiO4 (II)). Coagulation (i.e., sticking) of the aggregates was not observed. Low-velocity collisions resulted in restitution (i.e., bouncing), and at higher velocities, a transition from restitution to fragmentation was observed at ν ∼ 1 m/s for ZrSiO4 (I), as well as at ν ∼ 4 m/s for Aerosil 200. For ZrSiO4 (II), fragmentation at ν ∼ 4 m/s was found in two cases only. Due to the lower transition velocity, the fragmentation of ZrSiO4 (I) was investigated in more detail. The abundance of smaller fragments increases with increasing velocity and with decreasing impact parameter. At ν ∼ 4 m/s, the fragment numbers follow a power law mass distribution v (m)dm ∼ m-9/8dm. Extrapolation of the fragment mass distribution for catastrophic collisions between equal-sized aggregates were performed using a simple fragmentation model based on the following assumptions: (1) power law mass distribution between the constituent particle mass and the aggregate mass, (2) fragments have constant free surface energies per unit surface area, and (3) impact parameter-dependent efficiency for the transition of kinetic collision energy into free surface energy of the fragments. This model predicts a complete disintegration of the ZrSiO4 (I) aggregates into their building blocks for collision velocities of ≥50 m/s. For aggregates consisting of van der Waals-bonded constituent particles of 0.1 μm radii, these catastrophic collision velocities are much smaller and are predicted to be ∼3 m/s. These are typical velocities for the preplanetary nebula, so catastrophic fragmentations could be frequent events if aggregates in the solar nebula formed due to weak surface forces.Low-velocity aggregate-aggregate collisions play an important role for the developement of aggregate sizes during the first stages of accumulation of solid bodies in the preplanetary nebula. To study such collisions, an experimental setup was developed where two millimeter-sized dust aggregates collide in vacuum with relative velocities between ∼0.15 and ∼4 m sec-1. The impact parameters of the collisions are arbitrary so that central collisions as well as grazing collisions can be investigated. Two types of aggregates were used, (1) ZrSiO4 with constituent particle sizes ≤1 μm and 74% porosity and (2) Aerosil 200 (SiO2) with constituent particle sizes ∼12 nm and 97% porosity. 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These are typical velocities for the preplanetary nebula, so catastrophic fragmentations could be frequent events if aggregates in the solar nebula formed due to weak surface forces.**Experimental Investigations on Aggregate-Aggregate Collisions in the Early Solar Nebula**

## 1987 Kendall

26 February , McN.Alford, Birchall

### A new method for measuring the surface energy of solids

#### Experiments (surface energy of Titania/Silica), measure elastic modulus of sub-μm powder assemblies

Although the surface tension of liquids has been understood and measured since the time of Young1 and Laplace2, the surface energy of solids has eluded understanding and evaded measurement, despite its postulated importance to catalysis, crystal growth, colloidal behaviour, sintering and fracture. It is salutary to reflect that solid surface energies are even now more readily determined by theoretical argument than by experiment. Here we show that solid surface energies can be evaluated experimentally by measuring the elastic modulus of submicrometre powder assemblies, knowing the particle diameter, elastic modulus and volume fraction.

## 1983 Kawakami

10 July , Mizutani, Takagi, Kato, Kumazawa

### Impact experiments on ice

#### Collision experiments (cratering and fragmentation of pure ice targets, cylindrical projectiles (aluminium, poly-carbonate, teflon, pyrophyllite), 110 – 680 m/s), results: craters in ice about 2 times larger than in basalt in the same energy range, depth/diameter ratios (0.1 – 0.3) close to basalt values, specific energy for complete destruction of ice: ≈ 50 J/kg (two orders of magnitude lower than for basalt), very large impact craters (Callisto/Mimas) must have fractured the whole satellite

The results of cratering and fragmentation experiments on pure ice are reported. The projectiles used are cylindrical aluminum, poly-carbonate, teflon, and pyrophyllite fired at velocities between 110 m/sec and 680 m/sec, with kinetic energies at impact between 2 and 500 joules. Crater diameters (pit diameters) in the ice were about two times larger than craters in the same energy range in basalts. The ratios of (pit diameter)/(spall diameter) are about three and the ratios of (depth of crater)/(spall diameter) are between 0.1 and 0.3 which are close to the depth/diameter ratios observed in basalts. The crater diameter in ice is also well expressed as a single function of the ‘late-stage effective energy’ defined recently by Mizutani et al. [1983]. The specific energy for complete destruction of ice target is about 50 J/kg which is two orders of magnitude smaller than that of basalt. The present experimental data on cratering and fragmentation of ice show that the impacts associated with the largest craters on Callisto and Mimas must have severely fractured the whole satellites, and that those giant impacts with the kinetic energy of 1023 to 1027 joules probably affected significantly the evolution of the satellites.

## 1983 Haff

7 April

### Grain flow as a fluid-mechanical phenomenon

#### model to describe flow of sand grains between plates

The behaviour of granular material in motion is studied from a continuum point of view. Insofar as possible, individual grains are treated as the ‘molecules’ of a granular ‘fluid’. Besides the obvious contrast in shape, size and mass, a key difference between true molecules and grains is that collisions of the latter are inevitably inelastic. This, together with the fact that the fluctuation velocity may be comparable to the flow velocity, necessitates explicit incorporation of the energy equation, in addition to the continuity and momentum equations, into the theoretical description. Simple ‘microscopic ’ kinetic models are invoked for deriving expressions for the ‘coefficients’ of viscosity, thermal diffusivity and energy absorption due to collisions. The ‘coefficients’ are not constants, but are functions of the local state of the medium, and therefore depend on the local ‘temperature’ and density. In general the resulting equations are nonlinear and coupled. However, in the limit s << *d,* where s is the mean separation between neighbouring grain surfaces and d is a grain diameter, the above equations become linear and can be solved analytically. An important dependent variable, in this formulation, in addition to the flow velocity *u,* is the mean random fluctuation (‘thermal’) velocity *v* of an individual grain. With a sufficient flux of energy supplied to the system through the boundaries of the container, *v* can remain non-zero even in the absence of flow. The existence of a non-uniform is the means by which energy can be ‘conducted’ from one part of the system to another. Because grain collisions are inelastic, there is a natural (damping) lengthscale, governed by the value of *d,* which strongly influences the functional dependence of *v* on position. Several illustrative examples of static *(u* = 0) systems are solved. As an example of grain flow, various Couette-type problems are solved analytically. The pressure, shear stress, and ‘thermal’ velocity function *v* are all determined by the relative plate velocity *U* (and the boundary conditions). If *v* is set equal to zero at both plates, the pressure and stress are both proportional to *U2,* i.e. the fluid is non-Newtonian. However, if sufficient energy is supplied externally through the walls *(v* ≠0 there), then the forces become proportional to the first power of *U.* Some examples of Couette flow are given which emphasize the large effect on the grain system properties of even a tiny amount of inelasticity in grain-grain collisions. From these calculations it is suggested that, for the case of Couette flow, the flow of sand is supersonic over most of the region between the confining plates.

## 1980 Weidenschilling

### Dust to Planetesimals: Settling and Coagulation in the Solar Nebula

#### numerical model for computing simultaneous coagulation and settling (gravitational instability/non-Keplerian rotation of nebula), composite process forms km sized planetesimals

The behavior of solid particles in a low-mass solar nebula during settling to the central plane and the formation of planetesimals is examined. Gravitational instability in a dust layer and collisional accretion are considered as possible mechanisms of planetesimal formation. Non-Keplerian rotation of the nebula results in shear between the gas and a dust layer. This shear produces turbulence within the layer which inhibits gravitational instability, unless the mean particle size exceeds a critical value, ~ 1 cm at 1 AU. The size requirement is less stringent at larger heliocentric distances, suggesting a possible difference in planetesimal formation mechanisms between the inner and outer nebula. Coagulation of grains during settling is expected in the solar nebula environment. Van der Waals forces appear adequate to produce centimeter-sized aggregates. Growth is primarily due to sweepup of small particles by larger ones due to size-dependent settling velocities. A numerical model for computing simultaneous coagulation and settling is described. Relative velocities are determined by gas drag and the non-Keplerian rotation of the nebula. The settling is very nonhomologous. Most of the solid matter reaches the central plane as centimeter-sized aggregates in a few times 103 revolutions, but some remains suspended in the form of fine dust. Drag-induced relative velocities result in collisions. The growth of bodies in the central plane is initially rapid. After sizes reach ~ 103 cm, relative velocities decrease and the growth rate declines. Gas drag rapidly damps the out-of-plane motions of these intermediate-sized bodies. They settle into a thin layer which is subject to gravitational instability. Kilometer-sized planetesimals are formed by this composite process.

## 1977 Weidenschilling

19 February

### Aerodynamics of solid bodies in the solar nebula

#### drag force in solar nebula, collisions, size fractionation of bodies, velocities up to 104 cm/s (m sized objects)

In a centrally condensed solar nebula, the pressure gradient in the gas causes the nebula to rotate more slowly than the free orbital velocity. Drag forces cause the orbits of solid bodies to decay. Their motions have been investigated analytically and numerically for all applicable drag laws. The maximum radial velocity developed is independent of the drag law, and insensitive to the nebular mass. Results are presented for a variety of model nebulae. Radial velocities depend strongly on particle size, reaching values on the order of 104 cm/s for metre-sized objects. Possible consequences include: mixing of solid matter within the solar nebula on short timescales, collisions leading to rapid accumulation of planetesimals, fractionation of bodies by size or density, and production of regions of anomalous composition in the solar nebula.

# Dust + Chondrules

## 2012 Beitz

### Free collisions in a microgravity many-particle experiment

### II: The collision dynamics of dust-coated chondrules

#### microgravity collisions of dust, chondrules, chondrules with dust, dust coated chondrules (2 – 3 mm, 0.18 – 0.58 chondrule volume filling), few cm/s sticking velocity for dust coated chondrules, collisions with material mix (dust coated chondrule or chondrules colliding with dust) stickier than single materials, chondrules might act as catalyser for planetesimal growth

The formation of planetesimals in the early Solar System is hardly understood, and in particular the growth of dust aggregates above millimeter sizes has recently turned out to be a difficult task in our understanding (Zsom, A., Ormel, C.W., Güttler, C., Blum, J., Dullemond, C.P. [2010]. Astron. Astrophys., 513, A57). Laboratory experiments have shown that dust aggregates of these sizes stick to one another only at unreasonably low velocities. However, in the protoplanetary disk, millimeter-sized particles are known to have been ubiquitous. One can find relics of them in the form of solid chondrules as the main constituent of chondrites. Most of these chondrules were found to feature a fine-grained rim, which is hypothesized to have formed from accreting dust grains in the solar nebula. To study the influence of these dust-coated chondrules on the formation of chondrites and possibly planetesimals, we conducted collision experiments between millimeter-sized, dust-coated chondrule analogs at velocities of a few cm s-1. For 2 and 3 mm diameter chondrule analogs covered by dusty rims of a volume filling factor of 0.18 and 0.35–0.58, we found sticking velocities of a few cm s-1. This velocity is higher than the sticking velocity of dust aggregates of the same size. We therefore conclude that chondrules may be an important step towards a deeper understanding of the collisional growth of larger bodies. Moreover, we analyzed the collision behavior in an ensemble of dust aggregates and non-coated chondrule analogs. While neither the dust aggregates nor the solid chondrule analogs show sticking in collisions among their species, we found an enhanced sticking efficiency in collisions between the two constituents, which leads us to the conjecture that chondrules might act as ‘‘catalyzers’’ for the growth of larger bodies in the young Solar System.

# Ice, Dust, C

## 2002 Kouchi

15 January , Kudo, Nakano, Arakawa, Watanabe

### Rapid Growth of asteroids owing to very sticky interstellar organic grains

#### Experiments (organic covered ice and silicate grains), sticking threshold velocity 5m/s

We experimentally found interstellar grains covered with organic matter in an asteroid belt, and more importantly, the organic matter played an essential role in the formation of the asteroids. The sticking threshold velocity of 5 m/s of the millimeter-sized organic grains was several orders of magnitude higher than those of the coexisting silicate and ice grains. This indicated a very rapid coagulation of the very sticky organic grain aggregates and the formation of planetesimals in the asteroid region, covering even the early stage of the turbulent solar nebula. In contrast, there was no coagulation of the silicate and ice grains in the terrestrial and Jovian regions, respectively.

## 1993 Chokshi

### Dust Coagulation

#### silicate, icy, carbonaceous grains, numerical modelling, collision of two smooth/elastic/spherical grains, critical velocity (bouncing barrier) grain size dependent, coagulation too slow for efficient growth, but efficiently removes small grains from cloud

Two colliding dust particles can stick, bounce, fragment, melt or vaporize upon collision, depending on the relative velocity and material parameters. We have theoretically modeled the microphysics of the coagulation process in the collision of two, smooth, elastic, spherical grains. It is shown that sticking will occur when the relative collision velocity is less than a critical velocity, vcr, which depends on the grain size and the elastic properties and surface energy of the material. Critical relative velocities for coagulation have been evaluated as a function of grain sizes for silicate, icy, and carbonaceous grains. We find that vcr varies as R-5/6 where R is the radius of curvature of the colliding particles. Micron-sized grains require velocities below 10-2 cm s-1. Critical velocities also depend on the material properties (interface energy and elasticity) of the particles; thus small icy grains stick better than small quartz grains (vcr is ~ 2 x 103 cm s-1 vs. 102 cm s-1 for 1000 Å grains).

Realistic interstellar grains may be nonspherical and have core mantle structure and rough surfaces. In addition, plastic flow may also be of importance. The role of these effects in the coagulation process is examined. It is concluded that nonsphericity has only minor effect. Surface irregularities can limit coagulation considerably. For submicron-sized ice grains this may reduce the critical velocity by a factor ~ 3. For silicate and graphite grains this reduction may be much larger. While plastic deformation is very important in the collisions of centimeter-sized metal spheres, micron-sized grains have much higher yield strength, and their sticking will not be affected much. Finally, we briefly examine sticking in the collision of fluffy agglomerates.

Coagulation of interstellar grains in dense clouds is briefly discussed. We conclude that efficient coagulation requires coverage of grain cores by an icy grain mantle. Even then, coagulation will lead to only a doubling of the mass of a large (a > 1000 Å) grain within a dense core lifetime. Smaller grains can, however, be efficiently removed from the cloud by coagulation. Thus, coagulation can have a dramatic effect on the visible and, particularly, the UV portion of the extinction curve in dense clouds and on their IR spectrum.

# Ice + CO2

## 2016 Musiolik

7 June , Teiser, Jankowski, Wurm

### Ice grain collisions in comparison: CO2, H2O, and their mixtures

#### Collision experiments (CO2, H2O, 50 % mixture of both, 80 K, 1 mbar, 90 μm particle size), results: CO2 less sticky than H2O, more like silica, sticking threshold velocity increases with increasing water content

Collisions of ice particles play an important role in the formation of planetesimals and comets. In recent work, we showed that CO2 ice behaves like silicates in collisions. The resulting assumption was that it should therefore stick less efficiently than H2O ice. Within this paper, a quantification of the latter is presented. We used the same experimental setup to study collisions of pure CO2 ice, pure water ice, and 50% mixtures by mass between CO2 and water at 80 K, 1 mbar, and an average particle size of ∼90 μm. The results show a strong increase of the threshold velocity between sticking and bouncing with increasing water content. This supports the idea that water ice is favorable for early growth phases of planets in a zone within the H2O and the CO2 iceline.

## 2000 Arakawa

16 May , Higa, Leliwa-Kopystyński, Maeno

### Impact cratering of granular mixture targets made of H2O ice – CO2 ice – pyrophylite

#### Collision experiments (3-component targets to simulate cometary nucleus/planetary regolith (H2O:CO2: pyrophylite = 1:1:0.74), nonheated/heated by thermal radiation), samples formed layer structure inside, results: cratering pattern strongly depends on sample history, nonheated targets: crates with regular shape, ejected volume ~ impact energy E, depth ~E0.5, thermally stratified samples: large amount of loose sub-crustal material ejected (sometimes leading to small hole and huge cavity underneath (velocity dependent).

Experiments related to impacts onto three-component targets which could simulate cometary nucleus or planetary regolith cemented by ices are presented here. The impact velocities are from 133 to 632 m/s. The components are powdered mineral (pyrophylite), H2O ice, and CO2 ice mixed 1:1:0.74 by mass. The porosity of fresh samples is about 0.48. Two types of the samples were studied: nonheated samples and samples heated by thermal radiation. Within the samples a layered structure was formed. The cratering pattern strongly depended on the history of the samples. The craters formed in nonheated targets had regular shapes. The volume was easy to be determined and it was proportional to impact energy E. The crater depth scales as E0.5. Impacts on the thermally stratified target led to ejection of a large amount of material from the loose sub-crustal layer. For some particular interval of impact velocity a cratering pattern can demonstrate unusual properties: small hole through the rigid crust and considerable mass transfer (radially, outward of the impact point) within sub-crustal layer.

# CO2

## 2016 Musiolik

17 December 2015 , Teiser, Jankowski, Wurm

### COLLISIONS OF CO2 ICE GRAINS IN PLANET FORMATION

#### lab experiments CO2 (snowline ≈ 10 AU), 80 K, particles (≈ 100 m and target, 0 – 2.5 m/s, bouncing barrier ≈ 0.04 m/s, fragmentation > 1 m/s, analytical model for COR and fragmentation strength, collisional behaviour resembles dust, one order of magnitude smaller bouncing barrier, collisional growth most likely between H2O and CO2 snowlines

In protoplanetary disks, CO2 is solid ice beyond its snow line at ∼ 10AU. Due to its high abundance, it contributes heavily to the collisional evolution in this region of the disk. For the first time, we carried out laboratory collision experiments with CO2 ice particles and a CO2-covered wall at a temperature of 80 K. Collision velocities varied between 0 - 2.5 m/s. Particle sizes were on the order of ∼ 100 μm. We find a threshold velocity between the sticking and the bouncing regime at 0.04 m/s. Particles with greater velocities but below 1 m/s bounce off the wall. For yet greater velocities, fragmentation occurs. We give analytical models for the coefficients of restitution and fragmentation strength consistent with the experimental data. Set in context, our data show that CO2 ice and silicate dust resemble each other in the collisional behavior. Compared to water ice the sticking velocity is an order of magnitude smaller. One immediate consequence as example is that water ice particles mantled by CO2 ice lose any ”sticking advantage.” In this case, preferential planetesimal growth attributed to the sticking properties of water ice will be limited to the region between the H2O ice line and the CO2 ice line.

# CO

## 2013 Qi

### Imaging of the CO snow line in a solar nebula analog

#### chemical imaging of CO snowline (TW Hya, solar nebula analogue) with ALMA, observe N2H+, distribution in ring matches predicted position (30 AU) of CO snow line, helps to assess models of solar system

Planets form in the disks around young stars. Their formation efficiency and composition are intimately linked to the protoplanetary disk locations of “snow lines” of abundant volatiles. We present chemical imaging of the CO snow line in the disk around TW Hya, an analog of the solar nebula, using high spatial and spectral resolution Atacama Large Millimeter/Submillimeter Array (ALMA) observations of N2H+, a reactive ion present in large abundance only where CO is frozen out. The N2H+ emission is distributed in a large ring, with an inner radius that matches CO snow line model predictions. The extracted CO snow line radius of ∼ 30 AU helps to assess models of the formation dynamics of the Solar System, when combined with measurements of the bulk composition of planets and comets.

# C/O Ratio

## 2011 Öberg

### THE EFFECTS OF SNOWLINES ON C/O IN PLANETARY ATMOSPHERES

#### C/O ratio regulates chemistry in hot Jupiters, exoplanets show different C/O ratio from solar system, ratio depends on where w.r.t. the different snow lines the giant planets form, between H2O and CO snowline, most of O is present in icy grains

The C/O ratio is predicted to regulate the atmospheric chemistry in hot Jupiters. Recent observations suggest that some exoplanets, e.g., Wasp 12-b, have atmospheric C/O ratios substantially different from the solar value of 0.54. In this Letter, we present a mechanism that can produce such atmospheric deviations from the stellar C/O ratio. In protoplanetary disks, different snowlines of oxygen- and carbon-rich ices, especially water and carbon monoxide, will result in systematic variations in the C/O ratio both in the gas and in the condensed phases. In particular, between the H2O and CO snowlines most oxygen is present in icy grains—the building blocks of planetary cores in the core accretion model—while most carbon remains in the gas phase. This region is coincidental with the giant-planet-forming zone for a range of observed protoplanetary disks. Based on standard core accretion models of planet formation, gas giants that sweep up most of their atmospheres from disk gas outside of the water snowline will have a C/O ∼ 1, while atmospheres significantly contaminated by evaporating planetesimals will have a stellar or substellar C/O when formed at the same disk radius. The overall metallicity will also depend on the atmosphere formation mechanism, and exoplanetary atmospheric compositions may therefore provide constraints on where and how a specific planet formed.

# Surface Chemistry

## 2002 Fraser

### Laboratory surface astrophysics experiment

#### experiment designed to study surface ice chemistry in the lab (solid-gas interactions), 7 – 500 K, pressures 103 larger than in protoplanetary disks, gas composition H2 & CO, mass-spec/RAIRS/quartz crystal microbalance all in one chamber

In this article we describe the design and construction of a laboratory astrophysics experiment that recreates the harsh conditions of the Interstellar Medium (ISM) and is used to study the heterogeneous chemistry that occurs there. The Nottingham Surface Astrophysics Experiment is used to determine, empirically, accurately, and usually for the first time, key physical and chemical constants that are vital for modeling and understanding the ISM. It has been designed specifically to investigate gas–solid interactions under interstellar conditions. The pressure regime is ideally matched to molecular densities in dusty disks in protostellar or protoplanetary regions. The ultrahigh vacuum system is routinely capable of obtaining pressures that are only three orders of magnitude above those in the ISM, with similar relative concentrations of the two most abundant gases in such regions, H2 and CO, and an absence of any other major gas components. A short introduction describes the astronomical motivation behind this experiment. In Sec. II we then give details of the design, construction, and calibration of each component of the experiment. The cryostat system has far exceeded design expectations, and reaches temperatures between 7 and 500 K. This is comparable with the ISM, where dust temperatures from 10 K have been observed. Line-of-sight mass spectrometry, reflection absorption infrared spectroscopy, and quartz crystal microbalance mass measurements were combined into a single instrument for the first time. The instrument was carefully calibrated, and its control and data acquisition system was developed to ensure that experimental parameters are recorded as accurately as possible. In Sec. III we present some of the experimental results from this system that have not been published elsewhere. The results presented here demonstrate that the system can be used to determine desorption enthalpies, des*H*, bonding systems, and sticking probabilities between a variety of gases and ices common to the ISM. This instrument will greatly facilitate our understanding of surface processes that occur in the ISM, and allow us to investigate ‘‘mimic’’ ISM systems in a controlled environment. In this article we illustrate that laboratory surface astrophysics is an exciting and emerging area of research, and this instrument in particular will have a major impact through its contributions to both surface science and astronomy.

# ISM Molecules

## 2011 van Dishoeck

### Water in Star-forming Regions with the Herschel Space Observatory (WISH).

### I. Overview of Key Program and First Results

#### observations (80 sources), molecules: H2O/H218O/CO/13CO/C18O/OH+/H2O+/dust continuum, lack of water in cold gas, strong water emission from shocks, UV radiational heating of gas in outflow, H2O generally not the dominant coolant in warm dense gas around protostars

Water In Star-forming regions with Herschel (WISH) is a key program on the Herschel Space Observatory designed to probe the physical and chemical structures of young stellar objects using water and related molecules and to follow the water abundance from collapsing clouds to planet-forming disks. About 80 sources are targeted, covering a wide range of luminosities—from low (<1 L⊙) to high (>105 L⊙)—and a wide range of evolutionary stages—from cold prestellar cores to warm protostellar envelopes and outflows to disks around young stars. Both the HIFI and PACS instruments are used to observe a variety of lines of H2O, H218O and chemically related species at the source position and in small maps around the protostars and selected outflow positions. In addition, high-frequency lines of CO, 13CO, and C18O are obtained with Herschel and are complemented by ground-based observations of dust continuum, HDO, CO and its isotopologs, and other molecules to ensure a self-consistent data set for analysis. An overview of the scientific motivation and observational strategy of the program is given, together with the modeling approach and analysis tools that have been developed. Initial science results are presented. These include a lack of water in cold gas at abundances that are lower than most predictions, strong water emission from shocks in protostellar environments, the importance of UV radiation in heating the gas along outflow walls across the full range of luminosities, and surprisingly widespread detection of the chemically related hydrides OH+ and H2O+ in outflows and foreground gas. Quantitative estimates of the energy budget indicate that H2O is generally not the dominant coolant in the warm dense gas associated with protostars. Very deep limits on the cold gaseous water reservoir in the outer regions of protoplanetary disks are obtained that have profound implications for our understanding of grain growth and mixing in disks.

# Exoplanet Detections

## 1995 Mayor

### A Jupiter-mass companion to a solar-type star

#### hot Jupiter detection

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star’s radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

# Protoplanetary Disk Properties

## 2013 Kelling

26 July , Wurm

### ACCRETION THROUGH THE INNER EDGES OF PROTOPLANETARY DISKS BY A GIANT SOLID STATE PUMP

#### Illumination of inner edge of disk creates gas flow, local mass flow rates up to Ṁ = 10−5M⊙ yr−1

At the inner edge of a protoplanetary disk, solids are illuminated by stellar light. This illumination heats the solids and creates temperature gradients along their surfaces. Interactions with ambient gas molecules lead to a radial net gas flow. Every illuminated solid particle within the edge is an individual small gas pump transporting gas inward. In total, the inner edge can provide local mass flow rates as high as Ṁ = 10−5M⊙ yr−1.

## 2007 Desch

20 August

### Mass distribution and planet formation in the Solar Nebula

#### Disk model for Solar System, assume compact disk that is photoevaporated, solves problem that “minimum-mass” (assuming that giant planets swept up all material in their feeding zones) disk models have: Uranus and Neptune could not have grown to current size within lifetime of disk. This models derives planet masses within 10 % of actual masses, but only if Uranus and Neptune switched placed in early Solar System (also predicted by Nice model).

The surface density profile Σ(r) of the solar nebula protoplanetary disk is a fundamental input to all models of disk processes and evolution. Traditionally it is estimated by spreading out the augmented masses of the planets over the annuli in which the planets orbit today, the so-called minimum-mass solar nebula. Doing so implicitly assumes that the planets completely accreted all planetesimals in their feeding zones, but this assumption has not been tested. Indeed, models of the growth of Uranus and Neptune predict that these planets could *not* have grown to ≈10 M4 within the lifetime of the disk, even though they must have, to accrete H/He atmospheres. In this paper we adopt the starting positions of the planets in the ‘‘Nice’’ model of planetary dynamics (Tsiganis and coworkers), in which the solar system started in a much more compact configuration. We derive a surface density profile that is well approximated by the power law Σ(r) = 343(fp/0.5)-1(r/10 AU)-2.168 g cm-2, where fp is the fraction of the solid mass in the form of planetesimals. We show that this profile is inconsistent with a steady state accretion disk but is consistent with a steady state decretion disk that is being photoevaporated. We calculate the growth of planets in the context of this disk model and demonstrate for the first time that *all* of the giant planets can achieve their isolation masses and begin to accrete H/He atmospheres within the lifetime of the disk. The fit of our inferred Σ(r) to the augmented masses of the planets is excellent (<10%), but only if Uranus and Neptune swtiched places early in the solar system’s evolution, a possibility predicted by the Nice model.

## 1997 Chiang

3 July , Goldreich

### Spectral energy distributions of T Tauri stars with passive circumstellar disks

#### Hydrostatic, radiative equilibrium disk models, disks encased by thin layer of superheated dust grains, result: disks flare & absorb more stellar radiation than flat disks would, spectral features from dust grains in superheated layer appear in emission if disk is viewed nearly face-on

We derive hydrostatic, radiative equilibrium models for passive disks surrounding T Tauri stars. Each disk is encased by an optically thin layer of superheated dust grains. This layer reemits directly to space about half the stellar energy it absorbs. The other half is emitted inward and regulates the interior temperature of the disk. The heated disk flares. As a consequence, it absorbs more stellar radiation, especially at large radii, than a flat disk would. The portion of the spectral energy distribution contributed by the disk is fairly flat throughout the thermal infrared. At fixed frequency, the contribution from the surface layer exceeds that from the interior by about a factor 3 and is emitted at more than an order of magnitude greater radius. Spectral features from dust grains in the superheated layer appear in emission if the disk is viewed nearly face-on.

## 1997 Bell

3 April , Cassen, Klahr, Henning

### The structure and appearance of protostellar accretion disks: limits on disk flaring

#### Vertical structure models of protostellar α-law accretion disks: temperature dependence of opacity is crucial factor determining radial trends, most planet formation (0.5 – 3 M1 disks) occurred in environments unheated by stellar radiation, external heating enhances flaring, but inner disk will shield planet-forming regions in most cases

Vertical structure models are used to investigate the structure of protostellar, α-law, accretion disks. Conditions investigated cover a range of mass fluxes (10-9 to 10-5 M1 yr-1), viscous efficiencies (α = 10-2 and 10-4), and stellar masses (0.5 – 3 M1). Analytic formulae for midplane temperatures, optical depths, and volume and surface densities are derived and are shown to agree well with numerical results. The temperature dependence of the opacity is shown to be the crucial factor in determining radial trends. We also consider the effect on disk structure of illumination from a uniform field of radiation such as might be expected of a system immersed in a molecular cloud core or other star-forming environment: Tamb = 10, 20, and 100 K. Model results are compared to *Hubble Space Telescope* observations of HH30 and the Orion proplyds.

Disk shape is derived in both the Rosseland mean approximation and as viewed at particular wavelengths (λλ = 0.66, 2.2, 60, 100, 350, and 1000 μm). In regions where the opacity is an increasing function of temperature (as in the molecular regions where κfT2), the disk does not flare, but decreases in relative thickness with radius under both Rosseland mean and single wavelength approximations. The radius at which the disk becomes shadowed from central object illumination depends on radial mass flow and varies from a few tenths to about 5 au over the range of mass fluxes tested. This suggests that most planet formation occurred in environments unheated by stellar radiation. Viewing the system at any single wavelength increases the apparent flaring of the disk but leaves the shadow radius essentially unchanged. External heating further enhances flaring at large radii, but, except under extreme illumination (100 K), the inner disk will shield the planet-forming regions of all but the lowest mass flux disks from radiation originating near the origin such as from the star or from an FU Orionis outburst.

# Other Materials

## 2013 Krijt

1 October , Güttler, Heißelmann, Dominik, Tielens

### Energy dissipation in head-on collisions of spheres

#### Modelling COR (treat adhesion + viscoelasticity self-consistently, add up energy losses from deformation), viscoelasticity can increase enery dissipation (increasing sticking velocity), collisions above sticking velocity remain dissipative, comparison with lab experiments, model reproduced ε(v) relation observed in experiments (wide range of materials + particle sizes), adhesion + viscoelasticity + deformation are required for realistic model

Collisions between spheres are a common ingredient in a variety of scientific problems, and the coefficient of restitution (COR) is a key parameter to describe their outcome. We present a new collision model that treats adhesion and viscoelasticity self-consistently, while energy losses arising from plastic deformation are assumed to be additive. Results show that viscoelasticity can significantly increase the energy that is dissipated in a collision, enhancing the sticking velocity. Furthermore, collisions well above the sticking velocity remain dissipative. We systemically compare the model to a large and unbiased set of published laboratory experiments to show its general applicability. The model is well capable of reproducing the important relation between impact velocity and COR as measured in the experiments, covering a wide range of materials, particle sizes, and collision velocities. Furthermore, the fitting parameters from those curves provide physical parameters such as the surface energy, yield strength, and characteristic viscous relaxation time. Our results show that all three aspects—adhesion, viscoelastic dissipation and plastic deformation—are required for a proper description of the kinetic energy losses in sphere collisions.

## 2013 Güttler

29 May , Heißelmann, Blum, Krijt

### Normal Collisions of Spheres: A Literature Survey on Available Experiments

#### Summary of experimental data (COR for various materials), preparation for model paper, digitized data of all summarised experiments provided with the article

The central collision between two solid spheres or the normal collision between a sphere and a plate are important to understand in detail before studying more complex particle interactions. Models exist to describe this basic problem but are not always consistent with available experiments. An interesting benchmark to compare models and experiments is the relation between the normal coefficient of restitution e and the incident velocity v. In order to draw a broad comparison between experiments and models (Krijt, S., Güttler, C., Heißelmann, D., Tielens, A.G.G.M., Dominik, C., Energy dissipation in head-on collisions of spheres, submitted), we provide in this article an overview on the literature describing experiments on normal collisions, preferably providing data on e(v). We will briefly summarize our expectation on this relation according to an established collision model in order to classify these experiments. We will then provide an overview on experimental techniques, which we found in the summarized articles, as well as a listing of all experiments along with a description of the main features of these. The raw data on e(v) of the listed experiments were digitized and are provided with this article.

## 2009 Grasselli

3 June , Bossis, Goutallier

### Velocity-dependent restitution coefficient and granular cooling in microgravity

#### Microgravity experiments on granular cooling (vibrated granular medium, inelastic iron beads, 2D geometry, high-speed camera), results: COR (low v: ε increasing with v), time decay of energy in the system (cooling time much shorter than could be explained by constant or decreasing ε), better agreement between experiment and theory requires taking into account either rotational degree of freedom or v-dependence of ε.

We experimentally investigate the free cooling process occurring in a vibrated granular medium made of inelastic particles in a two-dimensional geometry. Experiments are realized in microgravity to cancel gravitational effects and recorded with the help of a high-speed camera. From the trajectories of the particles, obtained by image analysis, we can determine both the restitution coefficient and the time decay of the energy in the medium as soon as the vibration is cut off. We found evidence at low velocities of a positive slope of the restitution coefficient vs. the impact velocity, contrary to the usual approach where it only decreases with the velocity. We also found that the experimental cooling time is also much shorter than the one predicted on the basis of constant or decreasing restitution coefficient. A better agreement between theory and experiment is found if we take into account either the rotational degree of freedom or the velocity dependence of the coefficient of restitution.

## 2009 Sorace

5 November 2008 , Louge, Crozier, Law

### High apparent adhesion energy in the breakdown of normal restitution for binary impacts of small spheres at low speed

#### Collision experiments (head-on, two identical small particles, acrylic/ceramic/steel, suspended by resilient strands, impact velocity low enough for adhesion), COR lowered by adhesion, apparent adhesion surface energy larger than expected

We measure kinematic coefficients of normal restitution in head-on collisions of two identical small spheres of acrylic, ceramic or steel suspended by thin resilient strands at low enough impact speeds for adhesion to lower the restitution. We observe such reduction at speeds consistent with an apparent adhesion surface energy larger than expected.

## 2006 Reissaus

22 March , Waldemarsson, Blum, Clément, Llamas, Mutschke, Giovane

### Sticking efficiency of nanoparticles in high-velocity collisions with various target materials

#### Collision experiments (Al2O3 (5 – 50 nm) & C (10 – 20 nm) particles produced by laser ablation, impacting on target (C, Au, grease), 10-5 mbar, 1 km/s, sticking efficiency measured by microbalance), result: moderate to high sticking probabilities -> capture and retrieval of atmospheric particles feasible

In order to find reliable collector surfaces for the Mesospheric Aerosol – Genesis, Interaction and Composition (MAGIC) sounding rocket experiment, intended to collect atmospheric nanoparticles, the sticking efficiency of nanoparticles was measured on several targets of different materials. The nanoparticles were generated by a molecular beam apparatus in Jena, Germany, by laser ablation (Al2O3 particles, diameter 5–50 nm) and by laser pyrolysis (carbon particles, diameter 10–20 nm). In a vacuum environment (>10-5 mbar) the particles condensed from the gas phase, formed a particle beam, and were accelerated to ≈ 1 km/s. The sticking efficiency on the target materials carbon, gold and grease was measured by a microbalance. Results demonstrate moderate to high sticking probabilities. Thus, the capture and retrieval of atmospheric nanoparticles was found to be quantitatively feasible.

## 1994 Nuth

27 October , Berg, Faris, Wasilewski

### Magnetically Enhanced Coagulation of Very Small Iron Grains

#### Experiments (high coagulation efficiency of 20 nm-sized iron grains, produced in low-pressure H-atmosphere in magnetic field (100 Gauss) -> permanently magnetized), such grains could have been produced in solar nebula by procession of interstellar grains -> could act as “net” for sweeping up silicates -> aid planetesimal formation

Laboratory experiments, in which very small (∼20 nm) grains are produced in the presence of a magnetic field on the order of 100 Gauss in a low-pressure hydrogen atmosphere, have demonstrated that such smokes can become permanently magnetized. We show that magnetization results in an enormous enhancement in the coagulation efficiency of such materials even in the absence of external magnetic fields. Small iron grains should have been produced in the solar nebula by thermal processing of preexisting interstellar grains. If such processing occurred via high-energy electromagnetic events then the resultant magnetized grains could have triggered the formation of centimeter- to meter-sized protoplanetessimals by acting as "nets" capable of sweeping up nonconductive silicates suspended in the gas. It is possible that the presence of conductive fractal aggregates observed in modern-day protostellar disks could be explained by the enhanced coagulation efficiency of very small magnetized iron particles.

## 1993 Love

14 June , Hörz, Brownlee

### Target Porosity Effects in Impact Cratering and Collisional Disruption

#### Collision experiments ((soda lime glass projectiles, porous sintered glass targets, hypervelocity), results: Increased target porosity leads to deeper crater penetration, lower spall velocities, and greater localization of the impact damage, specific energy threshold for target destruction ~ (1-porosity)-3.6, experiments also produced melt-lined agglutinate crater pits

We present the results of a series of eight experimental hypervelocity impacts of soda lime glass projectiles into porous sintered aggregate glass targets with varying strengths and densities. Increased target porosity leads to deeper crater penetration, lower spall velocities, and greater localization of the impact damage. Rear surface spallation is also greatly reduced in porous targets. Estimates of the specific energy required to destroy targets of varying porosity indicates that this threshold is proportional to (1-porosity)-3.6, much greater than the dependence on unconfined compressive strength, and implying that the lifetimes of porous meteoroids and interplanetary dust particles against collisional disruption are longer than previously predicted. These experiments also produced melt-lined agglutinate crater pits, often well preserved despite total disruption of the target.

## 1984 Takagi

2 March , Mizutani, Kawakami

### Impact Fragmentation Experiments of Basalts and Pyrophyllites

#### Collision experiments (basalt/pyrophyllite targets (20 g – 3.3 kg), aluminum projectiles (2 – 20 g), 70 – 990 m/s), results: size distribution of fragments (power-law) dependent on nondimensional impact stress (PI = P0/Y · (L/R)3, P0 = peak shock pressure, Y = material strength of target, L = projectile size, R = target size) and on material (larger fragments for aluminum target than for brittle target at same PI)

Results of impact fragmentation experiments for basalts and pyrophyllites are reported. Aluminum cylindrical projectiles were impacted on cubic basalt and pyrophyllite targets at velocities of 70 to 990 m/sec. The targets and projectiles were 20 g to 3.3 kg and 2 to 20 g in weight respectively. Weights of the fragments produced by impacts were measured and the size distributions of fragments were examined. Data of the largest fragment mass (mL) normalized to the original target mass (Mt), mL/Mt, correlate better with the nondimensional impact stress, PI, a new scaling parameter introduced by H. Mizutani, Y. Takagi, and S. Kawakami (1984, in preparation) than the conventional projectile's kinetic energy per unit target mass, E/Mt, used in the previous studies. All the mL/Mt data for basalts obtained in the present study are summarized by mL/Mt = 2.95 × 10-2 PI-1 where PI = P0L3/YR3, P0 peak shock pressure, L projectile size, R = target size, and Y = material strength of target. For aluminum targets, however, the mL/Mt is 2.5 orders of magnitude larger than that for brittle targets at impacts with the same PI. Size distributions of fragments expressed in a log N - log (m/Mt) diagram are divided into three regimes bounded by two inflection points. In each regime the curve is expressed by N (>m/Mt) = A (m/Mt)-a. The slopes, a, of the log N - log (m/Mt) curves in the regimes of a large and a medium size range are positively correlated with the nondimensional impact stress, PI, and expressed as a = C3 + a3 log PI. The slopes, a, in the smallest size range are, on the other hand, nearly constant and have values of 0.5 to 0.7 (½ - 2/3). Present results indicate that the impact fragmentation is scaled well by the new scaling parameter, PI, of Mizutani, Takagi, and Kawakami and that the present experimental data may shed new light on planetary impact processes.