Planet Formation

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Spring 2010

Outline

1. Introduction
2. Core Accretion
   - Experimental Constraints
   - Theoretical Enhancements
3. Gravitational Instability
   - How Disks Fragment
   - Simulation
   - G.I. + Core Accretion

All That We Really Know: Planets Form in Disks

Important Constraints

- Lifetime
- Temperature
- Density
- Accretion

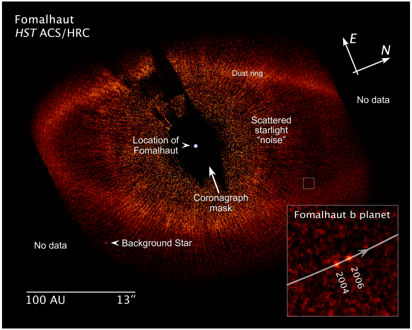

Image Credit: NASA

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Basic Picture

- Initial grain size
  $\Rightarrow$ stickiness
- Compaction
- Fragmentation?
- Bouncing?
- Rapid infall?

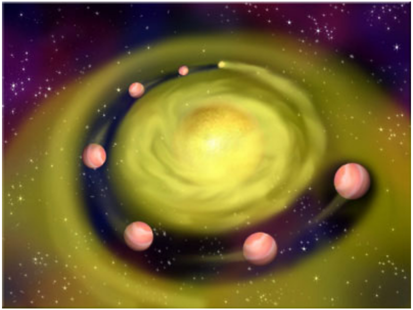


Image Credit: Meg Stalcup

Formation Barriers

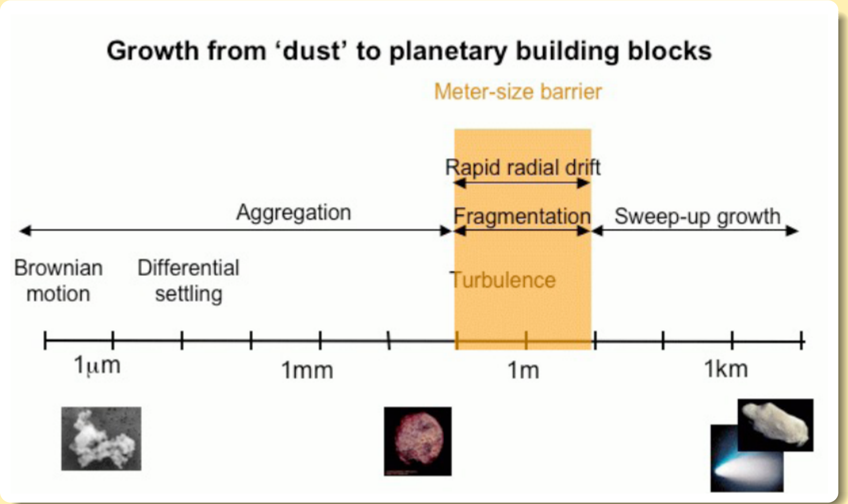


Image Credit: A. Zsom

Grain Composition

Need to Consider

- Oxides
- Metals
- Silicates
- Organic materials
- Ices

Well Studied

- SiO_2 (Silica)

Stickiness

Attractive Forces

- Nonmagnetic
- Uncharged
- Solid
- $\Rightarrow$ dipole-dipole only

- Sticking threshold ~ 1 m/s for µm-sized spheres
- Up to ~ 10 m/s for irregular-shapes

Collisions

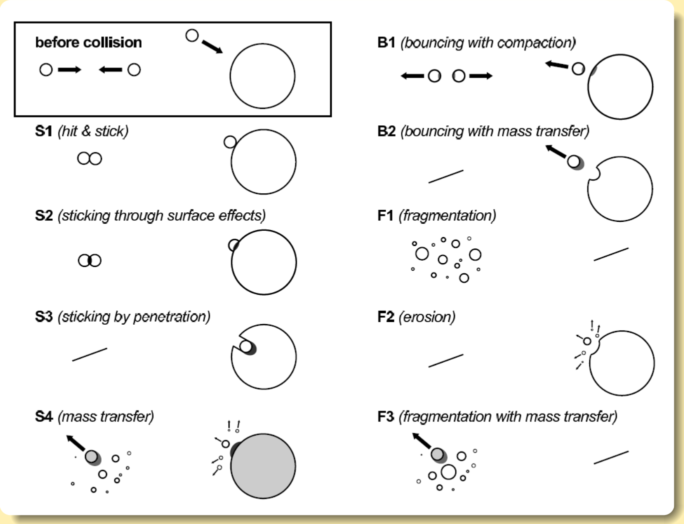


Image Credit: Zsom (2010)

Aggregation

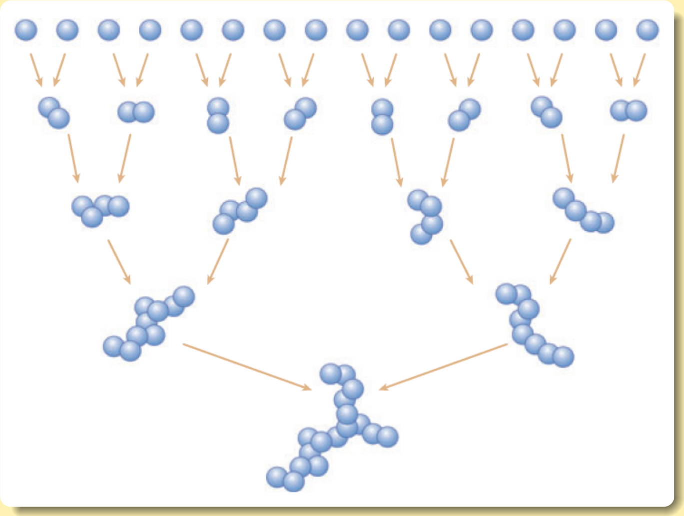
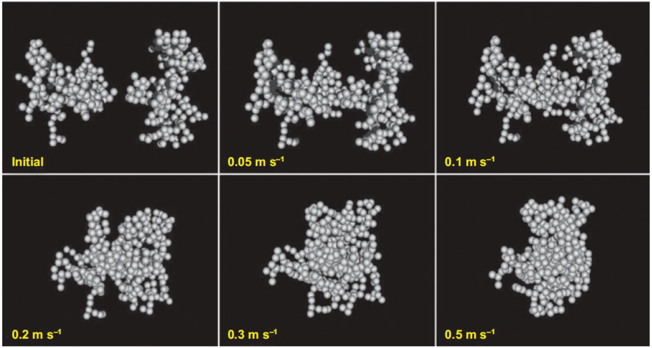


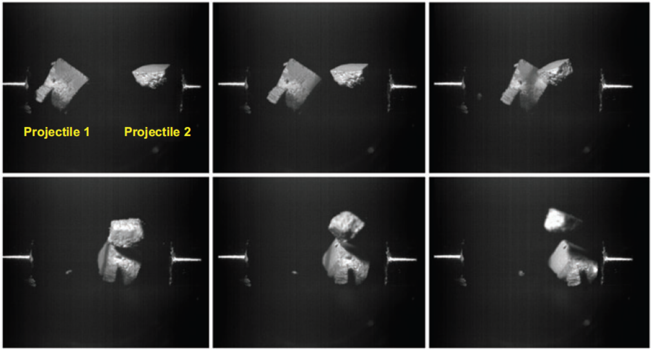
Image Credit: Blum & Wurm (2008)

Compaction



Blum & Wurm (2008), Figure 4: Compaction of fractal dust aggregates in mutual collisions (see Section 5.2). Molecular-dynamics simulations by D. Paszun & C. Dominik, University of Amsterdam. The upper left panel shows the initial dust aggregates before the collision. The subsequent panels show the results of the collisions with increasing velocity. The effect of restructuring and compaction is clearly visible.

Bouncing

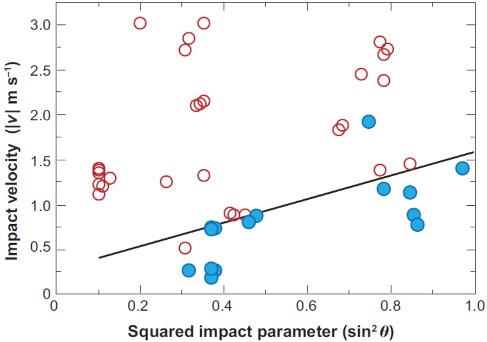


Blum & Wurm (2008), Figure 5: Bouncing of two irregular-shaped, nonfractal, but highly porous dust aggregates ($\phi = 0.15$) at a relative velocity of $\sim$0.4 m s^1 (see Section 5.3). The images were taken with a high-speed camera in a microgravity experiment onboard a parabolic-flight aircraft. The field of view is 24×20 mm^2. Figure by D. Heißelmann, H. Fraser & J. Blum (unpublished data).

Fragmentation

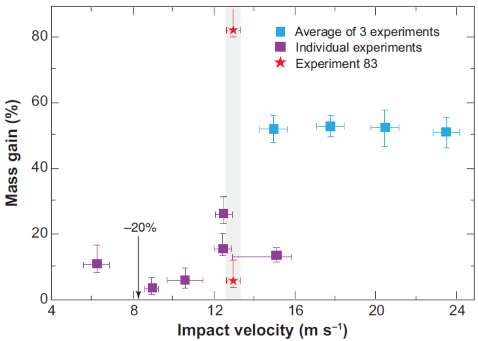
Blum & Wurm (2008), Figure 6: Fragmentation in aggregate-aggregate collisions (see Section 5.4). The figure shows the result of a smooth particle hydrodynamics simulation by Schäfer, Speith & Kley (2007) for two porous ice aggregates with a 1-m radius at 20 m s^{-1} collision velocity and an impact parameter of 1.2 m.

Sticking at High Velocity I



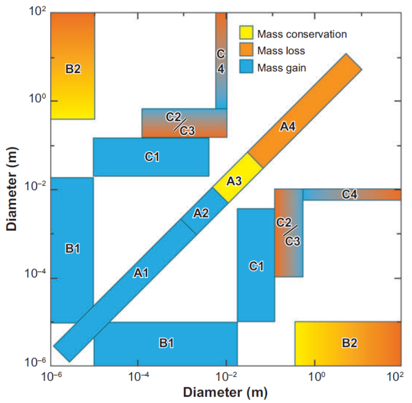
Blum & Wurm (2008), Figure 8: Bouncing (*filled circles*) and sticking (*open circles*) in impacts of millimeter-sized solid glass spheres with high-porosity ($\phi = 0.15$) centimeter-sized dust aggregates, consisting of α_3 particles (see Section 5.7). The solid line is an estimate of the threshold velocity between sticking and bouncing, which increases with increasing obliquity angle θ of the impact, denoted by the squared impact parameter $\sin^2(\theta)$ (J. Teiser & J. Blum, unpublished data).

Sticking at High Velocity II



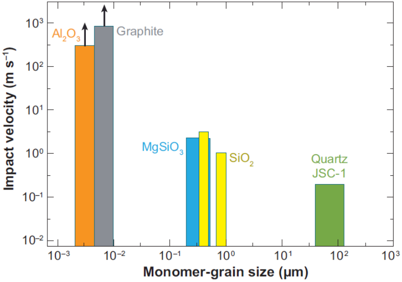
Blum & Wurm (2008), Figure 10: Accretion efficiency (the difference in target mass before and after an impact with respect to the projectile mass) in high-velocity impacts of compact dust aggregates into compact dust targets (see Section 5.9). Figure taken from Wurm, Paraskov & Krauss (2005b).

Overview of Laboratory Experiments



Blum & Wurm (2008), Figure 12: Overview of the results of the laboratory experiments described in Section 5. The blue, yellow, and orange boxes denote sticking, bouncing, and fragmentation for collisions between two protoplanetary dust aggregates of the sizes indicated at the axes of the diagram, respectively. Collision velocities were implicitly taken from Weidenschilling & Cuzzi (1993) (see Figure 1) for a minimum-mass solar nebula. It is clearly visible that direct growth of protoplanetary bodies $\gtrsim$ 10cm is not possible.

Effects of Dust Monomer Size



Blum & Wurm (2008), Figure 13: The sticking range for dust aggregates as a function of the dust-monomer size. The data in the nanometer-, micrometer-, and 100 μm-size range are taken from Reißaus et al. (2006), Blum & Wurm (2000), and Colwell (2003), respectively. Note that Reißaus et al. (2006) measured impacts (and sticking) at one velocity only so that their data for the nanometer-sized grains must be considered as lower limits. Whereas the experiments by Reißaus et al. (2006) and Blum & Wurm (2000) were performed with (fractal) dust-aggregate projectiles impacting solid targets, Colwell (2003) measured impacts of solid projectiles into nonfractal dust-aggregate targets.

How to Make Planetesimals?

Two Major Problems:

- Can't directly form dust aggregates $\gtrsim$ 10 cm
- Meter-sized bodies rapidly accrete onto star

Proposed Solutions:

- Extra-sticky grains
- Secondary accretion
- Trapping at Pressure Maxima (demo)

Sticky Grains & Secondary Accretion

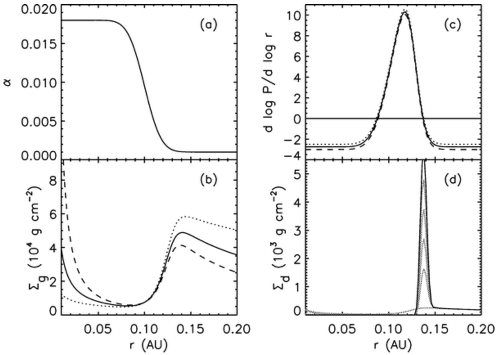
Increase Threshold Velocity or Effective Cross-Section

- Organic materials
- Ices
- Magnetic materials
- Charged dust

Recapture of Ejecta

- Aerodynamic re-accretion
- Electrostatic re-accretion

Pile-Up in the Dead Zone



Kretke & Lin (2007), Figure 1: Effect of an example variable $\alpha(r)$ shown in panel *a* on the gas properties. Panel *b* shows the corresponding steady state gas distribution with temperature profile $T = T_0 r^{-q}$ AU. The curves represent $q = 0.25$, 0.5, and 0.75 (dotted, solid, and dashed curves, respectively). Panel *c* shows the corresponding pressure gradient. Panel *d* shows the evolution of an initially well-mixed solid population after 500 orbits at 0.1 AU (gray lines show every 100 orbits).

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Stable Disk

- Random motions + centrifugal forces keep disk stable
- Toomre $Q \gtrsim 1$

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma}$$

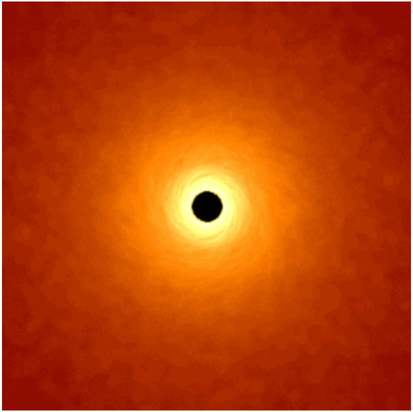


Image Credit: http://faculty.ucr.edu/~krice/

Spiral Arms Form

- Toomre $Q \lesssim 1$
- Spiral arms form
- Gas pressure supports spiral arms against further collapse
- Cooling time is long

$$t_{\rm cool} \gtrsim 1/\Omega$$

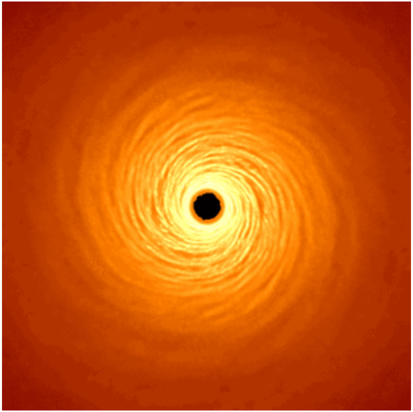


Image Credit: http://faculty.ucr.edu/~krice/

Spiral Arms Fragment

- Toomre $Q \lesssim 1$
- $t_{\text{cool}} \lesssim 1/\Omega$
- Pressure support is lost and spiral arms fragment
- Fragments may go on to form giant planetary embryos

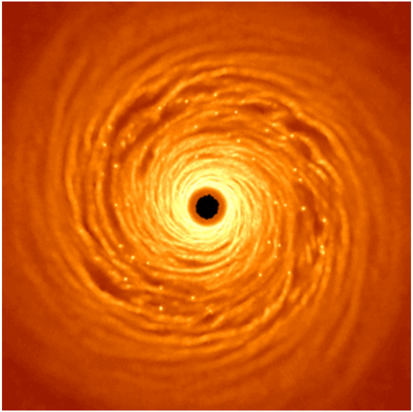


Image Credit: http://faculty.ucr.edu/~krice/

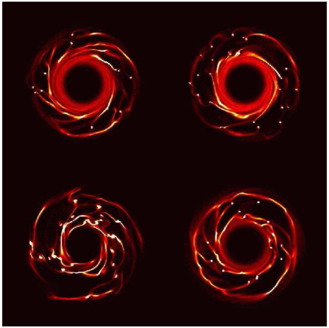
Numerical Techniques

- Hydrodynamics
  - Smoothed Particle Hydrodynamics
  - Grid-based: finite difference, piecewise parabolic method
- Radiative Physics
  - Fixed equation of state
  - Fixed t_{cool}
  - Flux-limited diffusion
  - Analytic radiative transfer

Numerical Issues

- Resolution (space + time)
- Artificial treatment of shock-heating
- Coarseness of grid
  - Errors in self-gravity
  - Breaks Poison solvers
  - Can cause imbalances between pressure and gravity
- Boundary conditions
- Smoothing kernel is large fraction of a scale height

Code Comparison

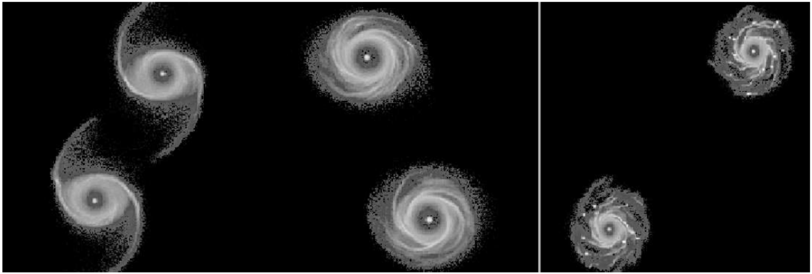


Durisen et al. (2007), Figure 5: Equatorial slice density maps of the disk in the test runs after about 100 yrs of evolution. The initial disk is 20 AU in diameter. From top left to bottom right are the results from GASOLINE and GADGET2 (both SPH codes), from the Indiana cylindrical-grid code, and from the AMR Cartesian-grid code FLASH. The SPH codes adopt the shear-reduced artificial viscosity of Balsara (1995).

Triggers for Instability

- Formation of massive disk during collapse of protostellar core
- Clumpy infall onto disk
- Local accumulation of mass
- Perturbations by binary companion
- Close encounter with other star/disk system

Effects of a Binary Companion



Durisen et al. (2007), Figure 3: Face-on density maps for two simulations of interacting $M = 0.1$ $M_\odot$ protoplanetary disks in binaries with $t_{\rm cool} = 0.5P_{\rm rot}$ viewed face-on. The binary in the left panel has a nearly circular binary orbit with an initial separation of 60 AU and is shown after first pericentric passage at 150 yrs (left) and then at 450 yrs (right). Large tidally induced spiral arms are visible at 150 yrs. The right panel shows a snapshot at 160 yrs from a simulation starting from an initial orbital separation that is twice as large. In this case, fragmentation into permanent clumps occurs after a few disk orbital times. Figures adapted from Mayer et al. (2005).

Effects of a Stellar Encounter

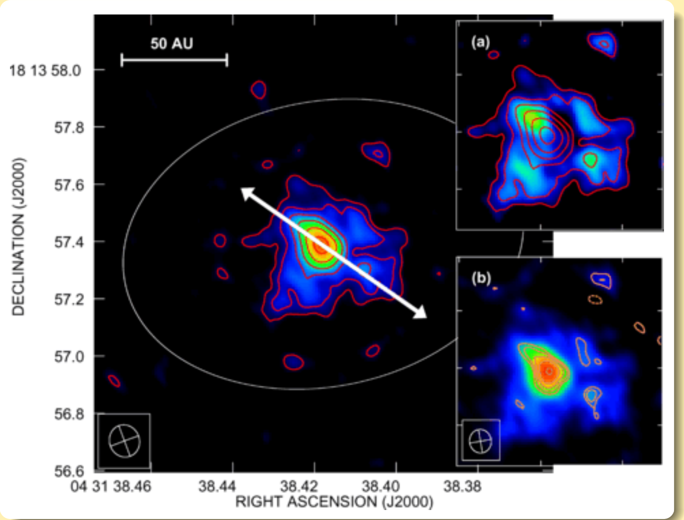
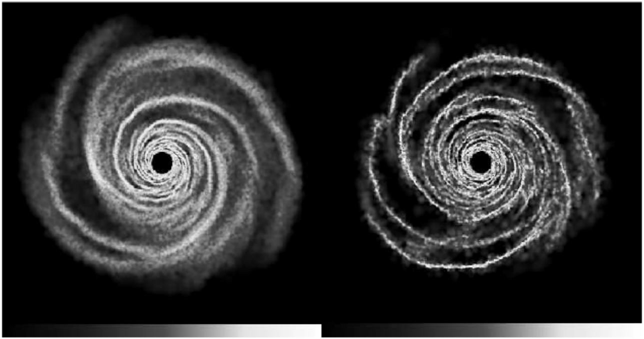


Image Credit: Greaves et al. (2008)

Interaction with Solids



Durisen et al. (2007), Figure 6: Surface density structure of particles embedded in a self-gravitating gas disk. a) The left-hand panel shows that the distribution of 10 m radius particles is similar to that of the gas disk, because these particles are not influenced strongly by gas drag. b) The right-hand panel illustrates that 50 cm particles are strongly influenced by gas drag and become concentrated into the GI-spirals with density enhancements of an order of magnitude or more. Figures adapted from Rice et al. (2004).

Summary

Core Accretion

- Explains terrestrial planets, asteroids, and comets (so it must work!)
- How do dust aggregates grow above ~ 10 cm?
- How do meter-sized objects avoid rapid infall?

Gravitational Instability

- Efficient at forming gas giants
- Needs massive disk (or at least local enhancements)
- Regulated by disk cooling (limits where instabilities can occur)
- Marginal instability could aid core accretion

References

- Blum, J., & Wurm, G. 2008, ARA&A, 46, 21
- Durisen, R. H., Boss, A. P., Mayer, L., Nelson, A. F., Quinn, T., & Rice, W. K. M. 2007, Protostars and Planets V, 607