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

J. Blum,1,* G. Wurm,2 S. Kempf,3 T. Poppe,1 H. Klahr,4 T. Kozasa,5 M. Rott,6 T. Henning,1 J. Dorschner,1 R. Schräpler,1 H. U. Keller,7 W. J. Markiewicz,7 I. Mann,7 B. A. S. Gustafson,8 F. Giovane,9 D. Neuhaus,10 H. Fechtig,3 E. Grün,3 B. Feuerbacher,10 H. Kochan,10 L. Ratke,10 A. El Goresy,11 G. Morfill,12 S. J. Weidenschilling,13 G. Schwachm,14 K. Metzlert,15 and W.-H. Ip16

1Astrophysical Institute and University Observatory, University of Jena, Schillergässchen 2-3, 07745 Jena, Germany
2Laboratory for Atmospheric and Space Physics, University of Colorado, Campus Box 392, Boulder, Colorado 80309-0392
3Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
4UCO/Lick Observatory, Kerr Hall, University of California, Santa Cruz, California 95064
5Division of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, Sapporo 060-0810, Japan
6Fachgebiet Raumfahrttechnik, Technische Universität München, Boltzmannstrasse 15, 85748 Garching, Germany
7Max-Planck-Institut für Aeronomie, Max-Planck-Straße 2, 37191 Katlenburg-Lindau, Germany
8Department of Astronomy, 211 Bryant Space Science Center, University of Florida, Gainesville, Florida 32611-2055
9Space Science Division, Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, D.C. 20375-5320
10Institut für Raumsimulation, Deutsches Zentrum für Luft- und Raumfahrt DLR, 51140 Köln, Germany
11Max-Planck-Institut für Chemie, Joh.-Joachim-Becher-Weg 27, 55128 Mainz, Germany
12Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, 85748 Garching, Germany
13Planetary Science Institute, 620 North Sixth Avenue, Tucson, Arizona 85705-8331
14ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
15Max-Planck-Institut für Aeronomie, Max-Planck-Straße 2, 37191 Katlenburg-Lindau, Germany
16Institute of Space Science, National Central University, Chung-Li, Taiwan, Republic of China

(Received 27 July 2000)

The outcome of the first stage of planetary formation, which is characterized by ballistic agglomeration of preplanetary dust grains due to Brownian motion in the free molecular flow regime of the solar nebula, is still somewhat speculative. We performed a microgravity experiment flown onboard the space shuttle in which we simulated, for the first time, the onset of free preplanetary dust accumulation and revealed the structures and growth rates of the first dust agglomerates in the young solar system. We find that a thermally aggregating swarm of dust particles evolves very rapidly and forms unexpected open-structured agglomerates.

PACS numbers: 96.35.Cp, 45.70.–n, 61.43.Hv, 81.10.Mx

It is now widely accepted that planets form from the nebula of gas and dust that comprises nascent solar systems. Inelastic, adhesive collisions between these dust particles eventually form kilometer-sized bodies, called planetesimals, which then collide under the influence of their mutual gravity to form planets [1–6]. After condensation of the micron-sized dust grains in the cooling gas, these initially collide with each other due to thermal (Brownian) motion, and, by adhesion due to van der Waals forces, form aggregates. The agglomeration rate of freshly condensed [7,8] preplanetary dust grains is determined by three factors: the collision cross section, the collision velocity, and the sticking probability of the dust particles, which are mutually interdependent. Laboratory experiments with micron-sized solid particles and dust aggregates thereof have shown that, for moderate collision velocities \( v_c \sim 1 \text{ m s}^{-1} \), the sticking probability is always unity [9–11]. The collision cross section and the collision velocity strongly depend on the morphology of the interacting preplanetary dust aggregates. Agglomerated, fluffy particles generally have a larger cross section than compact grains, but couple also much better to the gas motion, so that relative velocities between fluffy agglomerates are suppressed. The gas-grain interaction is best described by the dust particles' response time to the gas motion, \( \tau_f \). In the free molecular flow regime, \( \tau_f \propto \frac{m}{\sigma_a} \), where \( m \) and \( \sigma_a \) are the mass and the geometrical cross section (i.e., the projected area) of the dust aggregate. Aggregation models [1,12] for the Brownian motion-driven dust growth predict a scenario in which dust clusters of similar mass predominantly contribute to the agglomeration process. This leads to the evolution of a quasimonodisperse distribution of aggregate masses and to a relation between aggregate mass and size \( s \) of

\[
m \propto s^{D_f},
\]

with an exponent (“fractal dimension”) in the range of \( D_f \approx 1.8–2.1 \). For quasimonodisperse systems, the mean aggregate mass grows by a power law in time, \( m(t) \propto t^z \), and is related to the mass dependence of the collision cross section \( \sigma_c \propto m^\mu \) and the collision velocity \( v_c \propto m^\nu \) of the aggregating particles through \( \mu + \nu = \frac{z - 1}{2} \) (e.g., see the review in [13]). Here, \( z, \mu, \) and \( \nu \) are the respective exponents of the assumed power law functions for \( m(t), \sigma_c(m), \) and \( v_c(m) \). Fractal aggregates with \( D_f \approx 2 \) have \( \mu \approx 1, \) and ballistic thermal collisions yield \( \nu = -\frac{1}{2} \). Thus, we expect \( z = 2 \), which is supported by numerical simulations [12,13].
Aggregation due to Brownian motion in a cloud of micron-sized particles in rarefied gases has never been investigated experimentally, and there is no empirical evidence indicating how planetary formation begins and evolves. These agglomeration studies require an environment free from the overwhelming effect of sedimentation in Earth’s gravitational field. For the first experimental investigation of the initial preplanetary growth stage and for a test of the present models, we designed and built the Cosmic Dust Aggregation Experiment CODAG [14,15], which flew onboard STS-95 in October 1998. A sample of monodisperse, spherical SiO$_2$ (glass) dust grains (particle radii $s_0 = 0.95$ μm; monomer masses $m_0 = 7.2 \times 10^{-15}$ kg) was dispersed into a rarefied gas of pressure $p = 0.75$ mbar and temperature $T = 300$ K. Because of the low gas pressure, a molecular gas flow around the dust grains was present, and the particle motion close to the contact of two dust grains was ballistic (as opposed to the diffusive overall motion of the dust), so that the experimental conditions matched those in young solar systems very well.

The dust particle motion and the structure of the grown dust aggregates were analyzed with a stereo long-distance microscope with attached high-speed digital CCD cameras. The field of view of each of the two microscopes was $0.25 \times 0.25$ mm$^2$, with a spatial resolution of 1 μm, a depth of field of $\sim 80$ μm, and a temporal resolution of 5 ms.

In the experiment, the dust was not perfectly homogeneously distributed throughout the experiment chamber, but the dust particles were preferably found within two cloudlets, which were surrounded by basically dust-free zones. The cloudlets slowly drifted through the experiment chamber with a velocity of 0.4 mm s$^{-1}$ and crossed the field of view of the microscopes approximately $t = 55$ s and $t = 100$ s after the dust injection. Figure 1a shows microscope raw images of typical dust particles (top row) and the result of the image analysis (bottom row) by which we reduced each picture to its substantial information. For the experimental run of interest, we detected twelve well-focused dust aggregates, five of which were simultaneously imaged by both microscopes (see Fig. 1b for two-dimensional and Fig. 1c for three-dimensional representations of one of these aggregates). The two-dimensional images were used to derive the radius of gyration and the geometrical cross section of each of the aggregates. It turned out that the aggregates have an unexpectedly high average ratio of maximum to minimum radius of gyration of $\rho = 3.5$, which means that they are highly elongated. Published values for dust aggregates grown in a turbulent gas flow fall in the range $\rho = 2$–3 [16]. An analysis of the spatial orientation of the maximum radius of gyration showed that our dust aggregates were randomly oriented, i.e., unaligned. This means that the elongated structures are not the result of a preferential orientation of the dust grains.

For each of the detected particles, we also obtained positions of their respective centers of mass for five consecutive images with a time resolution of 5 ms. From these image sequences we derived for each particle, after the subtraction of the general cloudlet motion, one-dimensional displacement data $\Delta x$ with time bases of $\Delta t = 5, 10, 15, 20$ ms. The diffusion coefficient $D$ and the gas-grain response time $\tau_f$ are related by $D = (kT \tau_f)/m$, where $k$ denotes the Boltzmann constant. Classical diffusion theory yields

$$\langle \Delta x^2 \rangle = 2D\Delta t \left(1 - \frac{\tau_f}{\Delta t} + \frac{\tau_f}{\Delta t} \exp(-\Delta t/\tau_f)\right)$$

[17]. For $\Delta t \gg \tau_f$, this reduces to the well-known diffusion equation $\langle \Delta x^2 \rangle = 2D\Delta t$ [18]. Using Eq. (2), we converted the measured displacement data for the different

---

**FIG. 1.** Preplanetary dust analogs. (a) Raw images taken by the long-distance microscopes in the CODAG experiment (top row). Image analysis leads to the corresponding pictures in the bottom row from which the geometrical cross section, the radius of gyration, and the internal mass distribution were determined. Image sizes are $60 \times 60 \mu$m$^2$. (b) Same as (a) but for two mutually perpendicular projections of the same aggregate, simultaneously observed by two long-distance microscopes. (c) Three-dimensional reconstruction of the aggregate in (b). The radius of each of the constituent spheres is 0.95 μm. (d) Simulated ballistic cluster-cluster aggregates, each consisting of 32 monodisperse spheres and grown with a restricted normalized impact parameter of $\psi > 0.65$. The images are to scale with the images in (a) and (b) and were reduced to the spatial resolution of the CODAG optical instrument. Detailed analysis of the internal mass distribution shows an excellent agreement between these simulated aggregates and those measured with CODAG.
aggregate masses to mean square displacements for aggregates of unit mass $m_0$, which are plotted in Fig. 2 as a function of $\Delta t$ (data points with error bars). From the measurement of the gas-grain friction time for monomers [19] and from the mass-to-surface ratio of simulated aggregate structures (see below), we computed an expected aggregate response time of $\tau_f = 4.3 \pm 0.3$ ms. For long sampling times $\Delta t \gg \tau_f$, the grain motion is diffusive, i.e., $\langle \Delta x^2 \rangle \approx \Delta t$; on shorter time scales, i.e., during an encounter between two grains, the particle motion is ballistic, i.e., $\langle \Delta x^2 \rangle \propto (\Delta t)^2$.

FIG. 2. Dust particle motion in the CODAG experiment. Mean square particle displacement $\langle \Delta x^2 \rangle$ as a function of sampling time $\Delta t$ for the aggregates measured with the CODAG experiment (circles with error bars). For comparison with theoretical expectations, all displacements were corrected for their respective aggregate masses and were recomputed to monomer grains. The solid and the two dotted curves show the theoretical mean and range for pure diffusive motion with the expected value for the gas-grain response time $\tau_f = 4.3 \pm 0.3$ ms. For long sampling times $\Delta t \gg \tau_f$, the grain motion is diffusive, i.e., $\langle \Delta x^2 \rangle \approx \Delta t$; on shorter time scales, i.e., during an encounter between two grains, the particle motion is ballistic, i.e., $\langle \Delta x^2 \rangle \propto (\Delta t)^2$.

mass distributions of the experimental aggregates do not match those of the BCCA aggregates. We interpret this deviation of the expected from the observed aggregate structures as being due to the influence of the hitherto neglected stochastic thermal rotation of the aggregates during a close approach. In the case of linear chains, the mean thermal circumference velocity is a factor of $\sqrt{3}$ larger than the mean thermal linear velocity of the chain aggregate. Qualitatively, the effect of thermal rotation is that the first contact of two aggregates being on a central collision course will take place between their outer constituents rather than their central parts. Therefore, the effective impact parameter of collisions with rotating aggregates will deviate from the theoretical value of central collisions of nonrotating aggregates. If we define the normalized impact parameter $\psi$ such that central collisions have $\psi = 0$ and grazing collisions occur at $\psi = 1$, a slight restriction of the BCCA algorithm in the impact parameter space, $\psi > 0.65$, breaks the symmetry and produces aggregates whose internal mass distributions are in excellent agreement with those of the experimental aggregates. Examples of the simulated aggregates as they would appear in the CODAG microscope images are given in Fig. 1d.

One objective of the numerical simulations was to determine the mass-size relation [Eq. (1)] of the dust aggregates stemming from the ballistic thermal growth process. For the analog aggregates with $\psi > 0.65$, we determined $D_f = 1.3$. The ratio between mass and geometrical cross section is almost independent of the aggregate mass, and we get for the simulated aggregates $\tau_f \approx n_0^{0.06}$. Moreover, the numerical simulations allowed us to derive the masses of the observed aggregates from their geometrical cross sections by using the ratio between mass and geometrical cross section of the simulated aggregates. In Fig. 3a, the so-derived masses of the experimental aggregates are plotted versus the time of their occurrence after the dust injection (open circles).

With these aggregate masses and the known observational volumes, we determined the monomer number density in each of the two cloudlets. It turned out that both cloudlets had identical monomer number densities of $n_0 = 1 \times 10^{12}$ m$^{-3}$. The rectangular boxes in Fig. 3a represent the $1\sigma$ error of the mean aggregate mass in each of the cloudlets as well as the uncertainty of the mean time determinations.

For the derivation of the mass growth curve, the initial condition of the experiment needs to be known. Since there was no particle detection for $t < 50$ s, we performed control experiments in the laboratory, which showed that to a good approximation we can set $m(0) = (2 \pm 1)m_0$.

With the data in Fig. 3a, we cannot distinguish between an asymptotic growth of the form $m \propto t^2$ (solid line in Fig. 3a), as suggested by numerical simulations [12] and an exponential growth $m \propto \exp(\gamma t)$ (dashed line in Fig. 3a). The former is expected if the collision cross section between the aggregates is given by $\sigma_0 \propto m$; the latter requires $\sigma_c \propto s^2 \propto m^{2/D_f}$ [13]. It is up to future models
section is exponential mass growth which is expected if the collision cross
experiments in the laboratory. The dashed curve represents an
left corner of the diagram) was determined by calibration ex-
dotted lines). The initial condition (rectangular box in the lower
mean mass as well as the uncertainty of the mean time determi-
ations for each of the two cloudlets (confined by the vertical
motion-driven agglomeration proceeds rather rapidly and
leads to previously unexpected open-structured, fractal
dust aggregates with narrow mass distribution functions.
Although electrostatic particle charging by solar irradia-
tion is negligible in the young solar system due to the high
opacity, other factors, such as magnetic fields, may affect
early grain growth. Therefore, our experimental results
are applicable for nonmagnetic dust grains only.

This work was supported by the German Space Agency
DLR.

FIG. 3. Dust aggregate masses in the CODAG experiment.
(a) Aggregate masses as a function of time after dust injection
in the CODAG experiment. The open circles show the individual
dust aggregates for which precise mass determinations
were made. The rectangular boxes represent the 1σ error of the
mean mass as well as the uncertainty of the mean time determi-
nations for each of the two cloudlets (confined by the vertical
dotted lines). The initial condition (rectangular box in the lower
left corner of the diagram) was determined by calibration ex-
periments in the laboratory. The dashed curve represents an
exponential mass growth which is expected if the collision cross
section is \( \sigma_c \propto s^{2} \propto m^{2/(D_f)} \), and the solid line has an asymptotic
slope of 2 and represents a relation \( \sigma_c \propto m \). Mind that both
curves are meant only to guide the reader’s eye. (b) Normal-
ized cumulative mass spectrum of the aggregates in the CODAG
experiment (open circles). To account for the different obser-
vation times, individual aggregate masses were extrapolated to
t = 100 s with a power law of slope 2, matching the mean
local slopes of the two curves in (a). The solid line is a least squares
fit to the data points and has a slope of 1.8.

to derive the collision cross section for aggregates with
arbitrary fractal dimensions and to compute the temporal
evolution of the mean aggregate mass for Brownian mo-
tion and rotation. Figure 3b shows the corresponding mass
spectrum of the observed dust aggregates. The data points
fall along a well-defined power law with an exponent of
2 − λ = 1.8. Thus, the mass spectrum reads

\[
n(m)dm \propto m^{-\lambda}dm, \tag{3}
\]

with \( \lambda = 0.2 \). The measured cumulative mass spectrum
compares very well with the mass spectrum computed in
[12], particularly for their highest monomer number den-
sity. A recent analysis of mass spectra derived by solv-
ing the coagulation equation also gives similar results [20].
Mass spectra with \( \lambda < 2 \) represent mass distributions that
are dominated by the highest mass in the spectrum. In the
mass distribution shown in Fig. 3b, 50% (90%) of the to-
tal mass are concentrated in aggregates whose masses are
higher than 68% (28%) of the maximum mass. Hence, the
mass distribution function in Brownian-motion-driven dust
aggregation can be considered as quasimonodisperse.

In this paper, we showed that the initial stage of plan-
etesimal formation in the solar nebula due to Brownian-
motion-driven agglomeration proceeds rather rapidly and
leads to previously unexpected open-structured, fractal
dust aggregates with narrow mass distribution functions.

[1] S. J. Weidenschilling and J. N. Cuzzi, in Protostars and
Planets III, edited by E. Levy and J. I. Lunine (University
stars and Planets IV, edited by V. Mannings, A. P. Boss, and
S. S. Russell (University of Arizona Press, Tucson, 2000),
p. 533.
published).
(2000).
(1999).
Physics, Chemistry, and the Natural Sciences (Springer-
Verlag, Berlin, 1985).
441 (1996).