PLANETS

The first movement

Jeff Cuzzi

How do large objects form from the dusty gas surrounding a young star? A simulation suggests that several familiar processes, among them gas turbulence and self-gravitation, might work together to get the job done.

Making planets is tricky, and probably takes several stages. First, tiny interstellar grains must accrete into mountain-sized objects massive enough to decouple from their cocoon of nebula gas. These objects probably then combine in collisions, growing ever larger, past asteroid-sized planetesimals and lunar-sized embryos, to full-blown planets. How the first stage of this process, primary accretion, works is a fundamental unsolved problem of planetary science. On page 1022 of this issue, Johansen *et al.*[1] show how a combination of previously studied processes, acting together, might be the answer.

Our understanding of how protoplanetary nebulae evolve is generally based on observations of regions where stars are forming today. But the domain near the midplane of a nebula, where large objects grow, is shrouded from observations at visual and infrared wavelengths by opaque dust at higher altitudes in the nebula. And for longer-wavelength studies, insufficient spatial resolution is a problem.

Fortunately, our Solar System provides us with actual samples of primary planetesimals, in the form of primitive meteorites from asteroids and, recently, a milligram of cometary material returned by NASA's Stardust mission[2]. These planetesimals consist mainly of millimetre-sized particles — silicate 'chondrules' and higher-temperature oxides — often individually melted by intense thermal pulses in the nebula[3]. The ages of these sand-sized grains, assessed from a growing body of radioisotope data, indicate that primary accretion was an inefficient process that took between 1 million and 3 million years[4].

Over such a long period, according to models, the density, temperature and composition of the nebula would have changed profoundly[5]. Centimetre-to-metre-sized particles would also have migrated long distances, redistributing the nebula's solid component relative to its gas[6]. The mineral composition of the particles changed with their environment, and the result was the pot-pourri of meteorite classes with differing ages, structures, chemistry and isotopic content that we see today. Working backwards from today's evidence to infer the environment and physics of the primary accretion process is a fascinating challenge.

Take turbulence, for instance. Tiny dust grains routinely seen floating far above the midplane of million-year-old protoplanetary disks beyond our Solar System, and crystalline silicate grains seen in abundance in cometary nuclei[2], can be explained if nebula turbulence transports them around. But just what process can provide the energy needed to maintain turbulent gas motions, which would be quickly damped by the viscosity of the gas, remains controversial.

One popular mechanism is magnetorotational instability, in which low-density, ionized nebula gas couples to ambient magnetic fields strongly enough that tiny velocity fluctuations are amplified[7]. It is unclear whether this type of turbulence can exist in the dense, neutral gas found in the inner regions of protoplanetary nebulae, but other types of instability might occur even if the nebula gas is not ionized (ref. 8 and references therein). Once a turbulent regime forms, its details are only weakly dependent on the driving process, much as was suggested by the Soviet mathematician Andrei Kolmogorov more than 60 years ago[9].

Johansen *et al.*[1] construct a computational model of a nebula in which magnetorotational instability (for example) drives realistic three-dimensional turbulence. They then follow the evolution of metre-sized boulders in the model. The turbulence induces relative velocities between particles, and leads to local fluctuations in gas pressure, often on fairly large scales. These pressure fluctuations affect the local gas velocity, and determine whether particles experience a head wind (and drift inwards towards the central star) or a tail wind (and drift outwards). Particles thus accumulate in radial pressure maxima, which come and go with the evolution of large, turbulent eddies. Metre-sized particles tend to accumulate the most, as their drift rate under pressure fluctuations is the fastest.

Some of these zones live long enough that the rapidly drifting, metre-sized particles can become dense enough to exceed the gas density. In this case, the particles accelerate the surrounding gas to their preferred (keplerian) orbital velocity. These dense clumps sweep up other particles, and so become ever more massive. Ultimately, some clumps become bound together by their own gravity and, presumably, remain so as the components of the clump migrate slowly towards their mutual centre of gravity and become dense rubble piles. In only a few orbit periods, the model sees large bound clumps emerging, some as massive as the largest body in the asteroid belt, the 900-kilometre-diameter Ceres.

Johansen *et al.*[1] are appropriately cautious about some remaining uncertainties, particularly several poorly understood 'geological' issues related to the mechanics of solids. Physical sticking is needed to create metre-sized particles initially, and inelastic collisions (in which kinetic energy is converted into other forms of energy) are needed to damp their random velocities.

Sticking seems likely for small particles because they collide at very low velocities[10]. But collisional velocities in turbulence may reach tens of metres per second for metre-sized particles[11,12], a value more likely to destroy the particles than to bind them together. Frequent disruption at this crucial stage would weaken the drift-concentration effect that provides the catalyst for growth in this model. Because of limited numerical resolution and uncertainties in the physical properties of realistic nebula particles, the results of this paper are preliminary in this regard, as the authors describe in their extensive online supplementary information. Both improved numerical models of the coupled dynamics of gas and particles and a better understanding of the mechanical properties of aggregates[13] are needed.

The processes described by Johansen *et al.* emphasize concentration of metre-sized boulders, which themselves grew merely by the sticking of smaller grains[10]. Thus, one of the longest-known aspects of primitive meteorites, their dominance by millimetre-scale particles that are highly sorted according to size[3], is left unexplained. A different kind of concentration process has been proposed to explain how millimetre-sized particles can be concentrated into dense zones in the nebula[12], but so far only qualitative ideas of how planetesimals might grow out of these zones have been advanced.

The answer could be that some combination of processes, each selecting a different particle size, acts simultaneously or sequentially, possibly in turbulent conditions. (Of course, the mechanism by which turbulence is maintained remains uncertain.) Whatever the final answer turns out to be, the results of Johansen and colleagues[1] indicate that future efforts devoted to developing more complex models of the interactions between particles and gas in the protoplanetary nebula will be a good investment. ■

Jeff Cuzzi is at the NASA Ames Research Center,
Moffett Field, California 94035, USA.
e-mail: jcuzzi@arc.nasa.gov

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