Measuring the cohesive force of meteorite fragments to identify the mobility of asteroids

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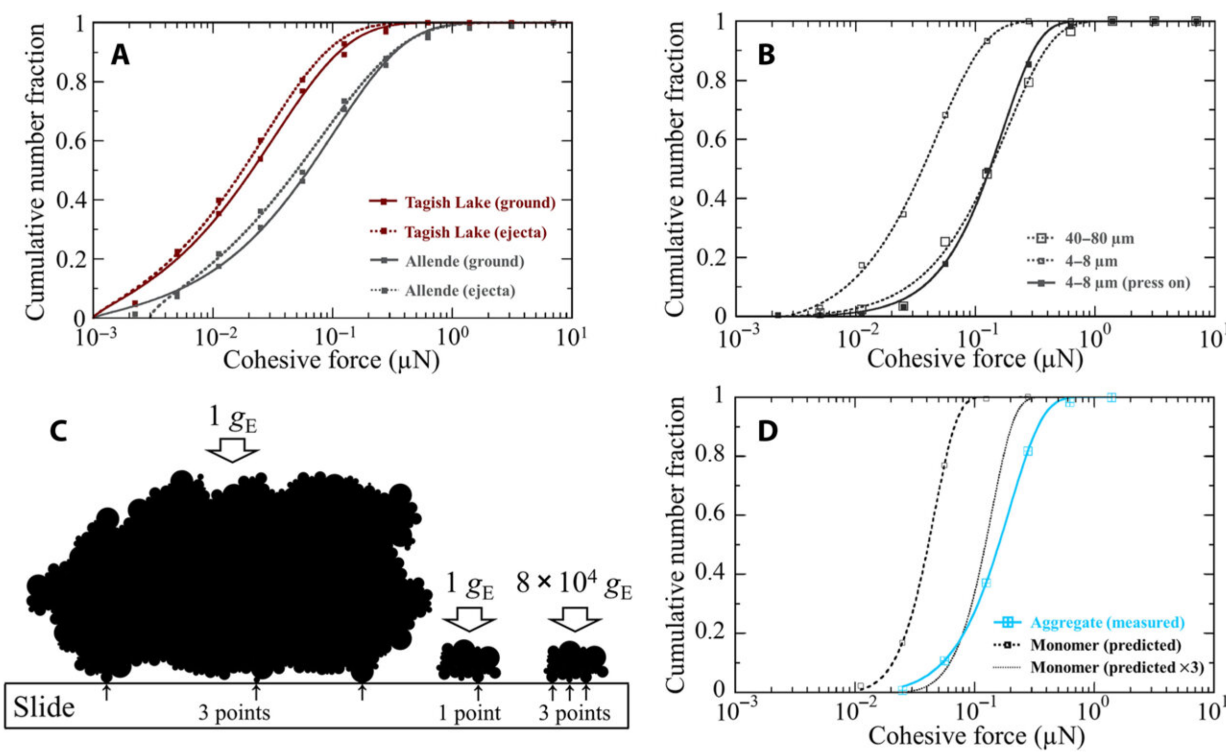
Credit: AI-generated image (disclaimer)

The cohesive force of asteroid particles influence microgravity and can be evaluated under several assumptions of particle size and their sensitivity to particle shape. Approximately hundreds of kilograms of material fall on to Earth's atmosphere daily from space, and filter down as tiny grains and fine dust. Many meteorites that reach Earth from space are pieces of asteroids.

In a new report now published in *Science Advances*, Yuuya Nagaashi and a research team in planetology at the Kobe University in Japan, conducted cohesive force measurements of meteorite fragments. The cohesive force of the asteroid particles were orders of magnitude smaller, resulting in the high mobility of asteroid surface particles identified during space exploration. For astrobiologists interested in the earliest history of Earth and the solar system, these particles that have survived almost unaltered offer significant information of the earliest period of the solar system's history.

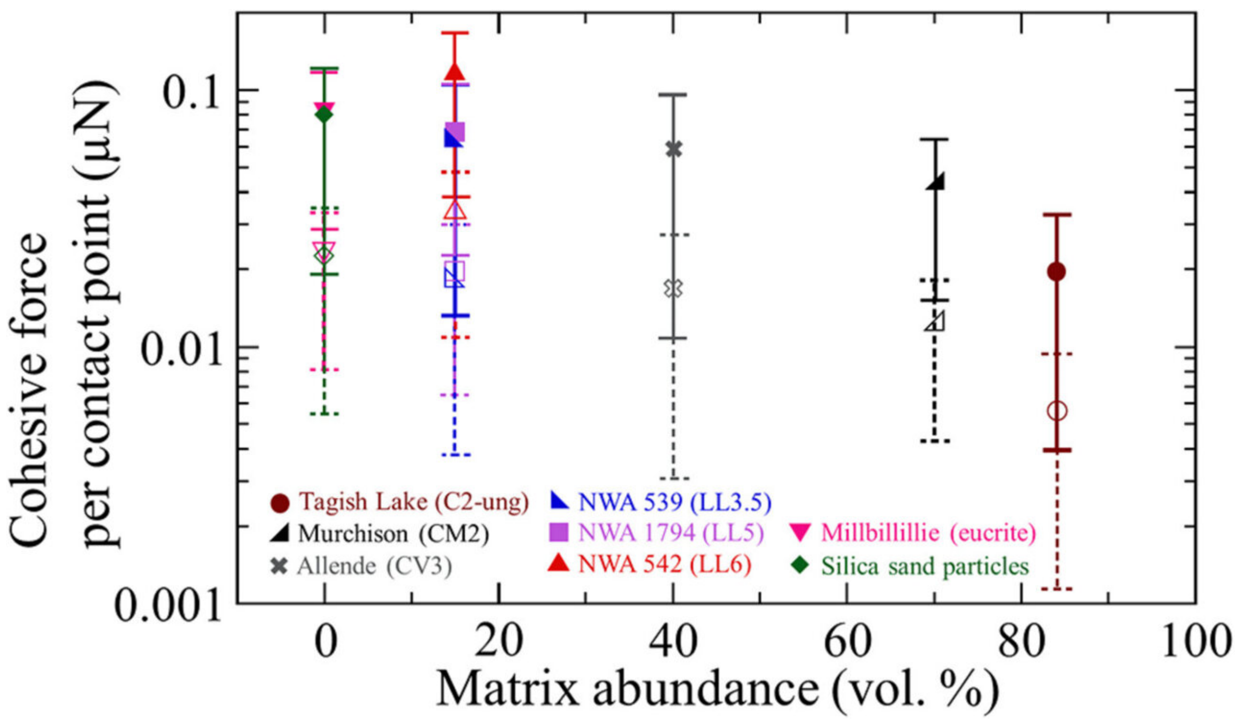


Cohesive force of particles. (A) Measured cohesive force of Allende and Tagish Lake meteorite fragments, prepared by a mortar and pestle or projectile impact, against a smooth glass slide under ambient conditions. The fitted curves were obtained on the basis of Eq. 3 in the article. (B) Measured cohesive force of tens-of-micrometer– and micrometer-sized Allende fragments against a stainless steel slide under ambient conditions. The value of the large fragments is approximately twice greater than that against the glass slide in (A), which might be consistent with the trend that the Hamaker constant of metals is greater than that of silica. (C) Schematic diagram of the contact states of meteorite fragments of different sizes against slides inferred from the cohesive-force measurements. The left fragment represents tens-of-micrometer–sized fragments at 1 gE, the middle fragment represents micrometer-sized fragments at 1 gE, and the right fragment represents micrometer-sized fragments at 8 × 104 gE. (D) Comparison of the measured cohesive force of aggregates tens of micrometers in size consisting of submicrometer-sized silica spheres against a glass slide under ambient conditions and the cohesive force estimated by the relationship obtained for the micrometer-sized silica spheres based on the size distribution of the constituent spheres. Solid curve indicates measurements, dashed curve indicates predictions, and thin dotted curve indicates three times the prediction. Credit: *Science Advances* (2023). DOI: 10.1126/sciadv.add3530

The fundamental forces behind the origin of planets

The onset of planetary formation relies on cohesive and adhesive forces between similar and different particle types that are key to understanding the evolutionary and eolian processes on planets. The cohesive force is a fundamental factor influencing coagulation processes and affects small bodies in microgravity environments. For example, it constitutes the fundamental force underlying particle migration due to the pressure of gas from a spacecraft or due to seismic wave accelerations resulting from an impact.

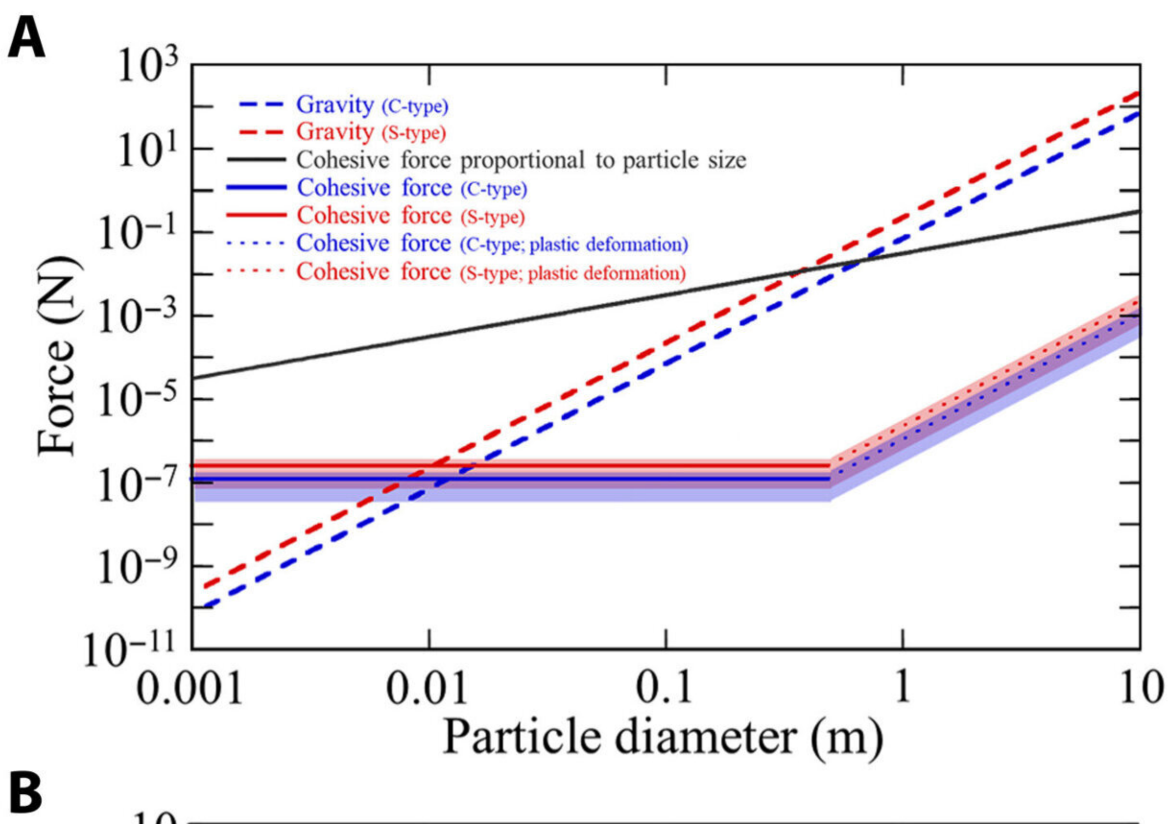
To conduct direct measurements of such cohesive forces, Nagaashi and colleagues used the centrifugal method and produced Allende and Tagish Lake carbonaceous chondrite fragments by using a motor and pestle, and obtained samples with well-characterized surface structures. The team conducted measurements under evacuated conditions or after heating them to observe the underlying impact.



Cohesive forces of meteorite fragments and abundance of matrix in the meteorites. Open symbols and dashed error bars indicate measurements under ambient conditions. The Tagish Lake and Allende meteorite values were obtained in this study; all other values are based on a previous study. The cohesive force per contact point between particles was corrected by one-half [because values obtained using the centrifugal method were measured between a particle and a slide] and one-third (because particles of tens of micrometers in size were in contact with a slide at approximately three points). Matrix abundance values were obtained from previous studies. Plots and error bars represent typical values and the range of the cumulative number fraction corresponding to 0.25 to 0.75, calculated by fitting Eq. 3 to the measurements, respectively. Closed symbols and solid error bars represent cohesive forces 3.5-fold greater than those measured under ambient conditions. The values are summarized in Table 1. Credit: *Science Advances* (2023). DOI: 10.1126/sciadv.add3530

Technical characterization of meteorite fragments

To study the shape of meteorite fragments, Nagaashi and the team used optical microscopy and confocal laser scanning microscopy. The outcomes did not distinguish between methods of fragmentation, nor did they indicate a significant difference in cohesive-force measurements among fragments of the same meteorite. However, when the team compared two types of meteorites, they noted the cohesive force of the Allende fragments to be several times greater than the Tagish Lake fragments.

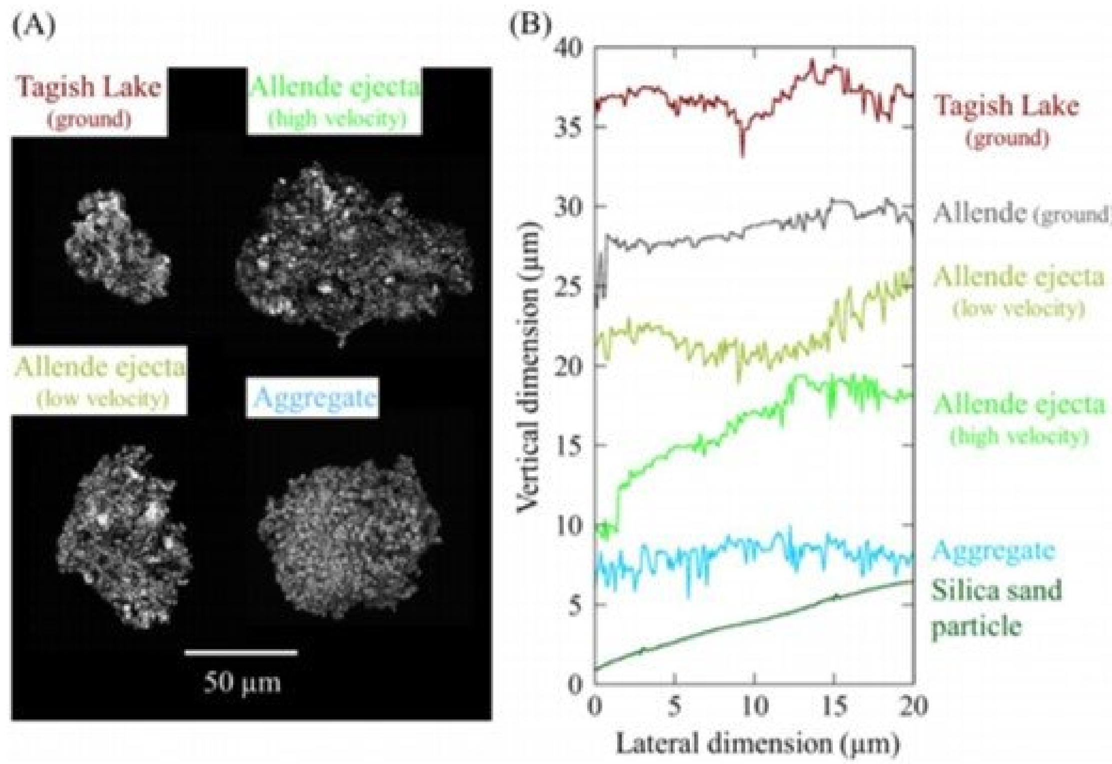


Low cohesive force and high surface mobility of asteroid particles. (A) Comparison of gravity and cohesive forces acting on particles on the surfaces of

C- and S-type asteroids with a diameter of 0.5 km. Dashed lines indicate gravity. Gray solid line indicates a cohesive force proportional to particle size. Blue and red solid lines indicate threefold those of typical cohesive forces per contact point listed. We assumed that typical cohesive forces for C- and S-type asteroids were the averages for carbonaceous and ordinary chondrites, respectively. Filled areas represent the predicted range of the cohesive force for particles with averaged typical cohesive forces. The range of the cohesive force corresponding to a cumulative number fraction of 0.25 to 0.75 was approximately 0.28 to 1.5 times the typical cohesive force on average. Dotted lines indicate the predicted cohesive forces, considering plastic deformation due to the particle's weight. (B) Pressure required to overcome gravity and cohesive force. Dashed curves indicate the case of the cohesive force proportional to the particle size. Solid curves indicate the case of the cohesive force obtained in this study. Credit: *Science Advances* (2023). DOI: 10.1126/sciadv.add3530

The researchers used atomic force microscopy to reveal the fine surface structures of meteorite fragments obtained from Tagish Lake samples and showed the cohesive forces to rely on surface structures at the sub-micron scale. When they heated the samples, the cohesive force increased by three-to-four manifolds due to surface water vapor evaporation and water composition reduction, resulting in a process of proportionally increased surface adhesion to reveal that cohesion in meteorite fragments depended on their surface topology.

Meteorite constituents are typically finer after undergoing underlying aqueous alterations and coarse after thermal alteration. Conventionally, scientists had detected the cohesive force of particles on asteroid surfaces based on van der Waals forces that were proportional to the particle size.

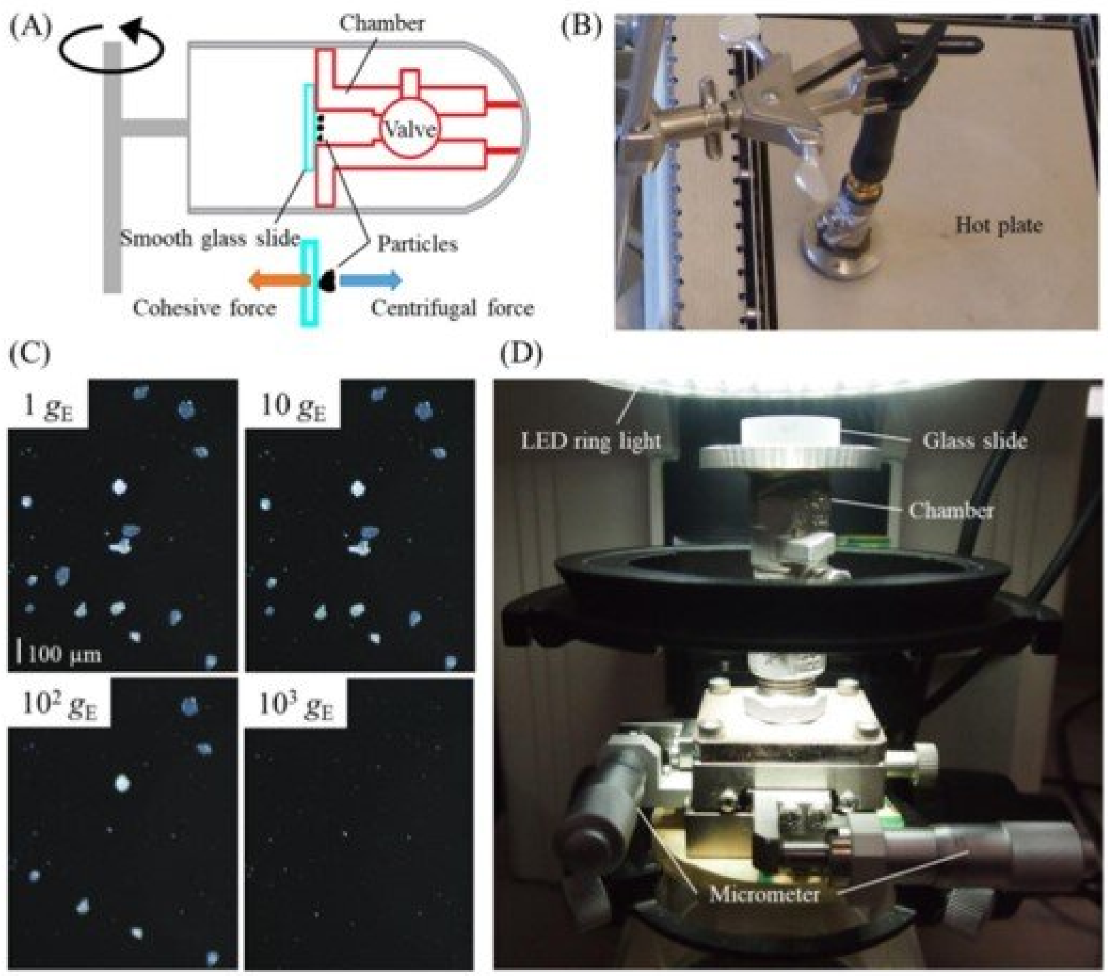


Microscopic morphology of particle. (A) Surface morphologies of each type of sample particle acquired via confocal laser scanning microscopy, and (B) one-dimensional profile extracted from the data. The horizontal axis shows the location along a line perpendicular to the line of sight, and the vertical axis shows the height. Data for the Allende ground fragment and silica sand particle are from a previous study. Credit: *Science Advances* (2023). DOI: 10.1126/sciadv.add3530

The Bond number

The contact points between the particles relied on the ratio between gravitational and cohesive forces, known as the Bond number. Scientists had previously assumed the cohesive force to be proportional to the particle size; however, the total cohesive force per fragment was smaller, indicating the mobility of the particles on a small asteroidal body.

Nagaashi and the team further studied the mobility of particles in a small asteroidal body relative to the pressure needed to overcome the force of gravity and adhesion and obtained values lower than expected. Such evidence for mass transfer was common to the asteroids Itokawa, Ryugu and Bennu, validating the theoretical estimates made in the study. Furthermore, the plastic deformation of particles can lead to greater cohesive force, which the researchers considered on asteroids by examining their surface appearance or topology.



Configuration of cohesive force measurements under reduced pressure. (A) Schematic diagram of centrifugal force application under reduced pressure. The cohesive force of particles was measured under reduced pressure in a space enclosed by a glass slide and a valved mini-vacuum chamber. (B) Particle heating was performed by placing a glass slide with particles in contact with a hot plate. (C) Optical microscope images of Allende fragments after heating (250 °C) and evacuation (~10−3 Pa) for 48 h on a slide before and after applying centrifugal accelerations of 10, 1020, and 103gE. Scale bar is 100 μm. (D) Configuration for optical microscope image acquisition. Micrometers were used to adjust the glass slide to acquire images of the same location. A light-emitting diode (LED) ring was used for imaging particles attached to the inner surface of the glass slide. Credit: *Science Advances* (2023). DOI: 10.1126/sciadv.add3530

Outlook

In this way, Yuuya Nagaashi and colleagues examined and characterized the cohesive or adhesion forces underlying meteorites or particles of asteroids. A general model of the solar system's formative process can be gleaned from the evidence obtained from meteorites and via telescopic investigations of asteroids. The work described here is focused on understanding the forces of cohesion and adhesion underlying the agglomeration of grains within a dusty layer to form clumps that accrued solid matter in large-scale planetesimals. Such bodies eventually grew rapidly to form embryonic planets.

The primary asteroid-belt located between Mars and Jupiter represent the surviving remnants of the inner solar system's early proto-planetary and planetary embryo population. Meteorites that originate from this asteroid-belt population provide detailed insight to measure the cohesive and adhesive forces underlying the origin of the solar system.

More information: Yuuya Nagaashi et al, High mobility of asteroid particles revealed by measured cohesive force of meteorite fragments, *Science Advances* (2023). DOI: 10.1126/sciadv.add3530

D. S. Lauretta et al, Spacecraft sample collection and subsurface excavation of asteroid (101955) Bennu, *Science* (2022). DOI: 10.1126/science.abm1018