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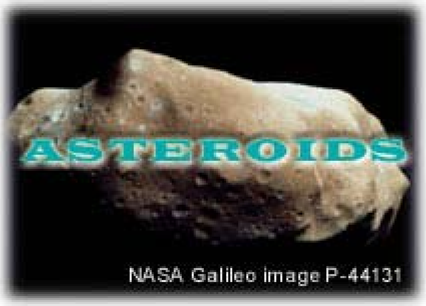

Honeycombed Asteroids

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Asteroids seem to have lower densities than the rocks scientists believe compose them. This implies that there is quite a bit of empty space inside the typical asteroid or small moon. Lionel Wilson (Lancaster University, UK), Klaus Keil (University of Hawaii), and Stanley Love (astronaut candidate, Johnson Space Center) investigated two possibilities for producing the high percentage of pore space. In one case they calculated that if an asteroid were broken apart and then reassembled, the resulting rubble pile would have a porosity of 20 to 40%, hence a density 20 to 40% lower than it had to begin with. They also calculated how fractures would form on bodies that contained water ice that was heated to steam, concluding that the fractures would be pervasive and, hence, decrease the density of the object.

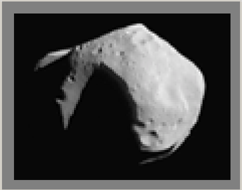
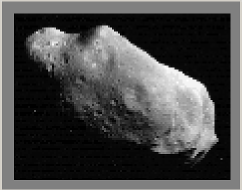
Reference:

Wilson, L., K. Keil, and S. J. Love, 1999, The Internal Structures and Densities of Asteroids, *Meteoritics and Planetary Science,* vol. 34, p. 479-483.

Asteroid and Meteorite Densities

We have fairly accurate measurements of the densities of four asteroid-sized bodies that have been visited by spacecraft: Phobos and Deimos, the small moons of Mars, and asteroids 243 Ida and 253 Mathilde. Each has been visited close enough by a spacecraft to allow calculation of its mass from the way it deflected the spacecraft from its course. Also, each of these bodies has been photographed well enough to be able to determine its volume. Because density is mass divided by volume, these data allow us to determine the densities of the objects. See the table below (Adapted from Wilson *et al.*, 1999.)

Observed bulk densities and implied bulk porosities of asteroids

Asteroid	Phobos	Deimos	253 Mathilde	243 Ida
Satellite photo				
Observed bulk density (g / cm ^{3})	1.5 - 2.2	1.3 - 1.7	1.3 ± 0.2	2.6 ± 0.5
Implied porosity (%)	6 - 35	28 - 43	36 - 53	11 - 42
Most closely related meteorite type, Porosity (%)	carbonaceous chondrite, 15-35	carbonaceous chondrite, 15-35	carbonaceous chondrite, 15-35	ordinary chondrite, 10

Density is a useful parameter. An asteroid made of pure iron-nickel metal, for example, would have a density of about 7.9 grams per cubic centimeter, so if we found an asteroid with such a high density we could conclude it was made of metallic iron. Of course, things are never that simple. An asteroid might have empty spaces in it (called pore spaces) which would lower the density in proportion to the percentage of pore spaces. Most planetary surface materials have pore spaces. Sand, for example, consists typically of about 40% pore spaces. (To get an idea of how much pore space a material can have, dump some sand into a volumetric beaker, up to say the 500 milliliters level. Then pour water from another calibrated container into the sand until you finally begin to get a puddle on top. You may be able to pour 200 milliliters of water into the 500 milliliters of sand.)

Even individual meteorites have some pore spaces. Guy Consolmagno SJ (Vatican Observatory) and Daniel Britt (University of Tennessee) have measured the density and porosity (the percentage of pore spaces is called porosity) of hundreds of meteorites and assembled a database of measurements made by other investigators [see PSRD supplement on: measuring density and porosity].

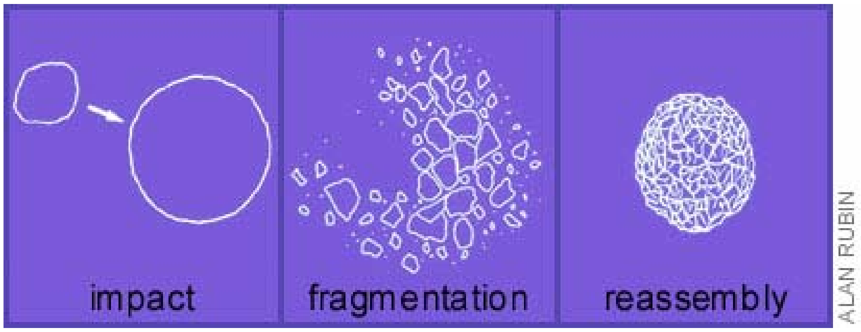
They find that the porosity of meteorites ranges from 5 to 35%. The porosity is in the form of cracks and spaces between mineral grains. Carbonaceous chondrites, which are dark rocks that contain carbon compounds (including organic chemicals) and water-bearing minerals, have porosities between 15% to 35%. In contrast, ordinary chondrites, which do not contain carbon compounds or water, have porosities of about 10%. Stony-iron meteorites have porosities of only about 5% and iron meteorites have essentially no porosity.

To compare the meteorite data with a given asteroid, we need to know what type of meteorite could have come from it. Wilson and coworkers did that by abopting a classification scheme used by astronomers. the classification is based on the amount and color of the light reflected off an asteroid, and on comparisons with the way powdered meteorite samples reflect light. Astronomers measuring the reflected light have classified 253 Mathilde as a C type asteroid, thought to be similar to carbonaceous chondrites. So, Wilson and colleagues assume 253 Mathilde is a carbonaceous chondrite, with a porosity of about 15 to 35% (see table above). Phobos and Deimos are classified as D or P types, which are darker than even the darkest carbonaceous chondrite, and do not correspond to any known type of meteorite. Nevertheless, Wilson assumes that the Martian moons are more likely to be similar to CI or CM carbonaceous chondrites, with porosity of 15-35%. 243 Ida is classified as an S type asteroid. What type of meteorite these correspond to depends on who one talks to: the issue is hotly contested. They could be either like ordinary chondrites or stony-iron meteorites. Wilson and colleagues assume 243 Ida is an ordinary chondrite.

Putting all this together, the two asteroids and two moons of Mars have somewhat lower densities, hence higher porosities, than do the meteorites to which they appear to be most closely related (see table above). This indicates that the asteroids and small moons have more empty spaces inside them than do small rocks removed from them. In other words, they appear to be gravitationally bound piles of rocks with empty spaces between the rocks.

Breaking Up Asteroids

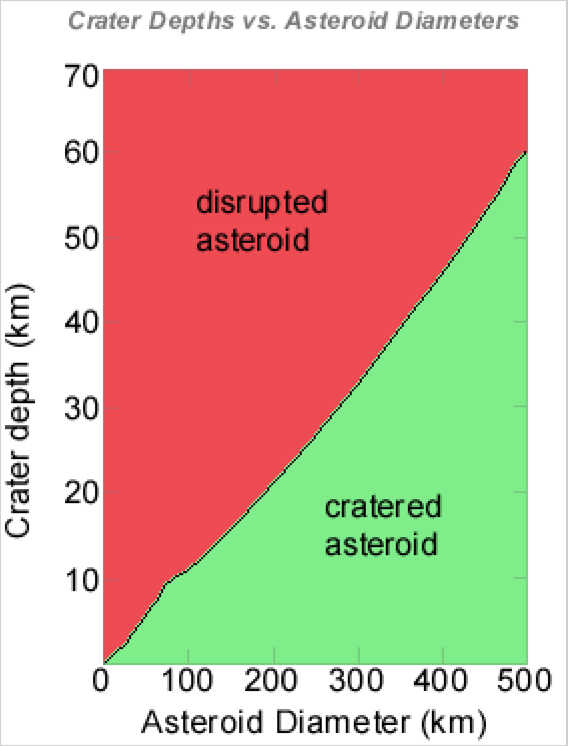
The idea that asteroids are rubble piles is not new. Theoretical studies of the evolution of asteroids by impacts indicate that for a large range in impact energies, the bodies break up, but the fragments do not move apart fast enough to escape each other. Their mutual gravity causes the fragments to promptly reassemble into a mixed-up, fragmented body; see graphic below.



Chondrite meteorites provide proof that this process actually happens. Some chondrites are called "regolith breccias." These are rocks reworked by impacts on the surfaces of asteroids. We know they formed in the uppermost part of the asteroid because regolith breccias contain gases implanted from the solar wind, which penetrate only micrometers into rock surfaces. These breccias also contain grains of metallic iron-nickel. It is possible to determine how fast these metallic particles cooled by measuring their compositions and sizes.

Numerous analyses indicate that in a given regolith breccia, the metallic particles cooled at rates ranging from 1 to 1000 degrees Celsius per million years. Using the laws of heat conductivity, we can calculate how deep a rock must be buried to cool at a given rate. The range of cooling rates of the particles in regolith breccias indicates original burial depths of a few kilometers (those cooling at 1000 degrees per million years) to 100 kilometers (those cooling at 1 degree per million years). Clearly, there has been a lot of scrambling of the asteroids on which these breccias formed!

At first glance, one would think that craters of different sizes could dig up rocks from a large range of depths and deposit them onto the surface where they could be incorporated into regolith breccias. It is not so easy, however. In 1987 my colleagues and I calculated that craters large enough to excavate rock from a depth of 60 kilometers would demolish asteroids smaller than 500 kilometers in diameter (see graph below). The easier way to deposit rocks from great depths and to mix them with rocks from shallow depths is to bust up the asteroid and reassemble it into a rubble pile.



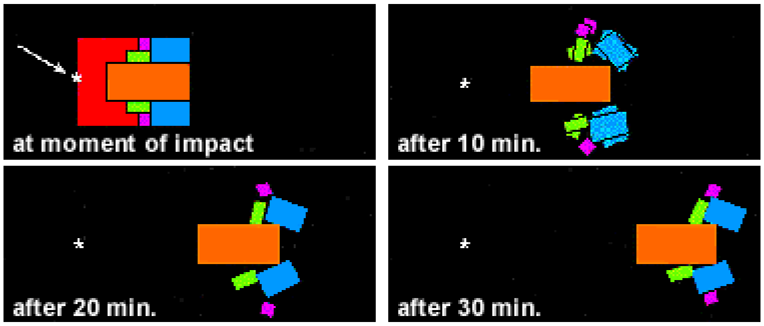
(adapted from Taylor et al., 1987.)

Graph showing the maximum depth a crater can be without breaking up an asteroid. Craters plotting beneath the line (in the green area) are not big enough to break up the asteroid; those above the line (red area) disrupt the asteroid. For example, on an asteroid 500 km in diameter, a crater deeper than 60 km would be so large that the asteroid would be demolished. Smaller craters would not break the asteroid apart, but would simply leave their telltale pock marks.

Increasing Porosity by Fragmentation and Reassembly

Lionel Wilson and his colleagues wondered if the high porosities (hence, low densities) of 243 Ida, 253 Mathilde, and the Martian moons, could be due to break up and reassembly of the bodies. To test this idea, Wilson wrote a computer program that followed the paths of numerous asteroid fragments after an impact large enough to demolish the asteroid. A critical piece of information he needed was the sizes and shapes of the fragments created by the disruption of an asteroid. For that information, Wilson used data from a series of experiments by Akiko Nakamura and Akira Fujiwara (Kyoto University, Japan). They broke up rock spheres by whacking them with projectiles moving at 3-4 kilometers per hour (appropriate for velocities in the asteroid belt), and examined the fragments produced.

Using Nakamura and Fujiwara's data as a guide, Wilson assumed that the asteroid broke up into elongated pieces with one large fragment, 4 smaller fragments, 32 still smaller, and 128 even smaller. About half the object breaks into even smaller pieces but most of them do not fall back onto the reassembled object. (A real asteroid, of course, would break up into millions of fragments, but computers can only keep track of a small number of particles. Too many fragments and the program will take forever to run.) The results are shown in the illustration below.



(adapted from Wilson et al., 1999.)

The blocks in this diagram, which vaguely resembles a cubist painting, represent the relative abundances and sizes of the fragments produced by a catastrophic impact. (Physicists frequently depict objects as cubes or spheres to make computation easier. They do, however, recognize that natural objects are not all cubes and spheres!) Orange is a single large fragment, blue the 4 smaller ones, green the 32 next smallest, purple the 128 next smallest, and red the smallest. The captions in the left corners show the time elapsed since the impact, which takes place at the asterisk by a projectile approaching from the direction of the arrow. Very few of the smallest fragments closest to the point of impact fall back to the shattered asteroid. The largest fragments, because they are accelerated the least, fall back first, followed by progressively smaller fragments, and most of the object is reassembled in about half an hour. Of course, it is missing a lot of mass - the red region that was fragmented into small pieces that were accelerated too fast by the impact to return to the scene of the crime.

Wilson and colleagues needed to determine the porosity of a reconstructed object. No elaborate computer program or cubist illustrations were required for this. Wilson simply cut up a chunk of polystyrene (Styrofoam®) into a range of sizes, with the number of fragments increasing as the size decreased (as in his computer calculations and in Nakamura and Fujiwara's experiments). He dumped the pieces into a beaker, putting the largest particles in first, then the smaller ones, and finally the smallest ones, to simulate the way his calculations indicated fragments fell onto the reassembling asteroid in the calculations. After adding the fragments, he gave the beaker a shake, then looked at the calibrations on the side of the beaker to determine the volume of the reassembled polystyrene "asteroid." Because he knew how much polystyrene he had used in making the fragments, the volume of empty space (the volume of pores) was simply the difference between the volume of the beaker taken up by the pile of fragments minus the volume of polystyrene particles. He repeated the measurement numerous times, and found that the porosity varied between 20% and 40%. This is about what Wilson and his co-authors estimated for the porosity of 243 Ida, 253 Mathilde, and the Martian moons.

Double Bubble, Toil and Trouble

Wilson and his colleagues also examined another way to increase the porosity of a small asteroid that originally contained lots of water ice mixed with rock. When such a mixture is heated (by decay of radioactive elements, for example), the water reacts with the rocky grains and forms hydrated minerals, releasing hydrogen gas, and possibly other gases as well. Wilson's calculations indicate that these gases would build up faster than they could escape because the outer parts of the asteroid may have had solid ice layers and the interior was compacted. As a result, the pressure built up, eventually exceeding the strength of the surrounding rock, causing cracks to form. This process may have caused pervasive fracturing of the interiors of asteroids, greatly increasing their porosities. Wilson estimates that this cracking mechanism could have operated in asteroids smaller than about 50 kilometers. Higher pressure inside larger asteroids prevented fracturing.

Rubble Piles

These latest results, which build on a great deal of work during the past 15-20 years, suggest that most asteroids are gravitationally bound rubble piles. This may make future mining of asteroids easier than if they were solid rock. It might also make it more difficult to predict the trajectories of fragments if earthlings try to blow up an asteroid headed for our planet.

We will soon be able to do another test of the rubble-pile hypothesis. The NEAR spacecraft will visit the asteroid 433 Eros early in 2000. Sensors onboard NEAR will try to determine the mineralogy and chemical composition of Eros, from which we will be able to estimate the asteroid's density if it were solid rock. The rubble-pile idea predicts that Eros will have a density much lower than the rock it is composed of.

Additional Resources

Asteroids: from The Nine Planets by Bill Arnett.

Asteroids: from the National Space Science Data Center.

Consolmagno, G. J. and D. T. Britt, 1998, The Density and Porosity of Meteorites from the Vatican Collection, *Meteoritics and Planetary Science,* vol. 33, p. 1231-1241.

Galileo Mission homepage.

Nakamura, A. and A. Fujiwara, 1991, Velocity Distribution of Fragments Formed in a Simulated Collisional Disruption, *Icarus,* vol. 92, p. 132-146.

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Taylor, G. J., P. Maggiore, E. R. D. Scott, A. E. Rubin, and K. Keil, 1987, Original Structures, and Fragmentation and Reassembly Histories of Asteroids: Evidence from Meteorites, *Icarus,* vol. 69, p. 1-13.

Wilson, L., K. Keil, and S. J. Love, 1999, The Internal Structures and Densities of Asteroids, *Meteoritics and Planetary Science,* vol. 34, p. 479-483.

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