Brazil nuts help unlock the asteroid's boulder mystery

G. V. Punyakoti

Asteroids are lumps of rocks – relics from the planet formation era, revolving around the Sun in a specific orbit between Mars and Jupiter. Japanese spacecraft *Hayabusa* was launched in May 2003 to fetch a small sample from the asteroid Itokawa (named after the Japanese rocket scientist Hideo Itokawa[1]). When *Hayabusa* was stationed close to Itokawa in September 2005, it acquired extensive photographs of the asteroid. Eventually, despite many technical glitches, the space probe grazed Itokawa's surface, collected tiny grains of asteroid material, and dramatically returned to Earth[2] in June 2010. It was the very first time an asteroid was sampled and photographed in such grand detail.

Scientists were especially puzzled by the photographs captured by *Hayabusa*, as they revealed an unusually large number of huge boulders on the asteroid's surface. On a planetary surface such as the Earth, we generally find a specific power law distribution of the size of the boulders: there are relatively fewer large boulders and a huge number of smaller ones. Surprisingly, this was not the case on Itokawa; obviously, it was a challenge to explain the disproportionately higher number of large boulders! In fact, Eros, another asteroid similarly photographed by NASA's NEAR *Shoemaker* space probe, also exhibited a similar skewed distribution of boulders, hinting at a common pattern extant among the asteroids.

Boulders scattered on the surface of the asteroid (Figure 1) were initially thought to be fragments ejected when other bodies hit the asteroid. In which case, every smash would leave behind a crater as its imprint. However, volume of such impact craters on the surface of Itokawa did not match with that of the boulders; in fact the volume of total boulder exceeded that of total crater[3]. In other words, the observed boulders on the surface of Itokawa cannot be attributed to the impacts alone. While the crater–boulder volume discrepancy may be resolved by various ways[4,5], the peculiar pattern of the size distribution of boulders remained a puzzle: Why are there relatively more number of large boulders on the surface?

Mutsumura *et al.*[6] demonstrated a novel way to tackle this problem. They addressed the problem using the famous Brazil Nut Effect (BNE; Box 1). It has been shown that when a bowl of mixed nuts is constantly shaken, due to the granular convection or BNE, the bigger nuts rise to the surface while the smaller nuts settle underneath. Simply put, during the shake, smaller nuts slide under the bigger nuts and prevent the large ones from settling at the bottom; the process continues until the big ones sift to the top[7].

BNE was proposed as a potential mechanism to account for the observed skewed distribution[8] of boulders on asteroids: large boulders rise to the surface of an asteroid due to their seismic shaking, akin to the rise of large Brazil nuts in a shaken container of a mixture of nuts of different sizes. Researchers from the University of Dundee, University of Maryland College Park and University of Nice Sophia Antipolis, have now demonstrated how this effect could indeed be employed to explain the observed anomaly, through simulations using the N-body code PKDGRAV, which is a simulation algorithm adopted for particle collisions[6].

In the simulated experiment, 1800 small spheres of radius 1 cm and one large sphere of radius 3 cm, all with density akin to aluminium, were poured into a container. Initially, the large sphere was placed at the bottom and then the container was vertically vibrated above a certain threshold frequency. Gradually, the large sphere moved to the top and eventually reached the surface.

The next obvious step was to verify if BNE can indeed be employed to explain the observed pattern of boulder size distribution on Itokawa. As an initial step, they simulated the gravity of the Moon, Ceres, Itokawa and Eros and introduced oscillating frequencies that match the respective gravity conditions and found that the large particles rose to the surface. In particular, if the seismic shaking provided the oscillations that could lead to BNE, the size sorting of boulders on asteroids might be possible[10].

Matsumara and her associates estimated that the time for the boulders to arrive at the surface of the asteroids ranges anywhere between a few hours to a day, which requires a considerably long duration of vibration. They suggest that this can be attained through multiple impacts or long-lasting seismic shaking.

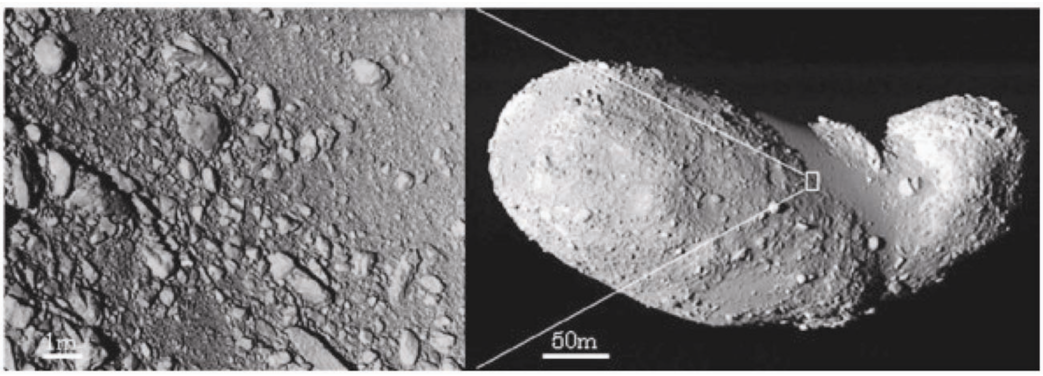

Figure 1. Asteroid Itokawa and its boulder strewn surface. The asteroid is about half a kilometer in length[2]. Image courtesy: JAXA (Japanese Aerospace Exploration Agency), ISAS.

Box 1. Brazil Nut Effect.

When a box of mixed nuts of different sizes is shaken continuously, larger among them such as Brazil-nuts rise to the surface while the smaller ones settle at the bottom; this process is termed Brazil Nut Effect (BNE). The process can even be seen in the kitchen; upon joggling the instant coffee powder container, the bigger coffee powder grains rise to the top while the fine powder moves to the bottom. The effect has been observed in a wide range of granular materials like grains, marbles, beads, powdered snow, coal, pile of rocks, etc. and women in India have been using this technique to sift out large stones from the grains in the winnow pans. The effect was reported in 1930 (ref. 8) and has since been extensively studied.

There are several ways to explain BNE: When a box of mixed nuts is shaken, small particles have the greatest energy and hence move around rapidly occupying empty spaces. Large nuts moving slower than the small nuts, are prevented from settling in regions occupied by smaller nuts and hence the large nuts gradually sift to the top[7]. Another way to understand this is through convection: due to shaking, the nuts are forced to move up and down within the confined spaces of the box leading to a net upward flow in the central region and a downward flow along the walls. Large nuts easily rise in the central zone but find it hard to move downward along the walls due to lack of enough space while the small ones owing to their size move downward easily. This process continues until the large nuts eventually rise and the small ones settle beneath the larger ones. The critical energy needed for this convection process is provided by the shaking of the box and the frequency of oscillations required to cause the effect, the critical threshold frequency, which in the study on Itokawa boulders, is shown to decrease with decrease in gravity.

Prabhu Nott points out that BNE is not predominant in large scale systems on the Earth's surface, because Earth's seismic activities are local and extremely transient, whereas the entire asteroid bounces during a collision and hence BNE can be observed on a large scale. 'Yet', he adds, 'the effect can be seen during an avalanche – largest rocks rise to the top owing to BNE and travel far, resulting in casualties'.

Thus, the strange size distribution pattern observed at present might be a consequence of BNE arising due to frequent jostling of the asteroids since their origin during the planet formation era!

However, simulations have been done assuming a container wall, whereas the asteroids do not have boundary walls for the boulders. Could this change the entire result for the asteroids? Matsumura and her team are studying such gaps in the explanation.

Prabhu Nott[7] (Chemical Engineering Department, Indian Institute of Science) says BNE has been observed in simulations with periodic boundaries, and in such situations, the effect depends only on particle diameter, gravitational acceleration and oscillation frequency. In other words, the lack of an impenetrable boundary may not drastically alter the conclusions drawn by Matsumara group for the asteroid boulders.

1. http://en.wikipedia.org/wiki/Hideo_Itokawa
2. http://www.bbc.co.uk/news/10285973
3. Fujiwara, A. *et al.*, *Science*, 2006, **312**, 1330–1334.
4. The unaccounted boulders could be powdered relics (regolith) of another small asteroid which could have crashed into Itokawa leaving its ruins (boulders) trapped on Itokawa's surface, wherein we expect boulders without craters.
5. Itokawa was formed due to the regrouping of fragments from an earlier parent asteroid which had cataclysmically disintegrated due to a collision, this could also account for boulders on the surface without craters: Michel, P. *et al.*, *A&A*, 2013, **554**, L1.
6. Matsumura, S. *et al.*, *MNRAS*, 2014, **443**, 3368–3380.
7. Based on an interview with Prof. Prabhu Nott, Chemical Engineering Department, IISc, 4 September 2014.
8. Miyamoto, H., *et al.*, *Science*, 2007, **316**(5827), 1011–1014.
9. http://jfi.uchicago.edu/granular/Brazilnut.html
10. e-mail correspondence with Soko Matsumura, 6 September 2014.

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G. V. Punyakoti, S. Ramseshan Fellow.
e-mail: punyakoti.gv@gmail.com