Dynamic Fragmentation, Asteroid Impacts and Meteorites from Mars

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Since meteorites were recognized as extraterrestrial in 1802, a number of strange specimens have been collected.

Shergotty, an 1865 fall, closely resembles a terrestrial basalt…
Chassigny, which fell in 1815 is mainly composed of olivine crystals

Slide width = 0.3 mm
The basalt-like appearance of these meteorites, and the lack of chondrules, raised suspicions in the early 1980s that they might come from a large planet. The discovery of a cumulate pyroxenite meteorite enhanced these suspicions.

Nakhla fell in Egypt in 1911
Shergottites, Nakhlites and Chassigny turned out to be much younger than most other meteorites.
The clincher, however, came from a meteorite collected from the Antarctic ice in 1979
Named EETA 79001, it contained telltale blobs of glass
That contained dissolved gases matching the Martian atmosphere almost perfectly.
Space exposure ages suggest only a few (6?) launch events in the past 20 million years.

**Figure 13.** Histogram of “ejection ages” (averages) of Martian meteorites (from calculations by Nyquist et al. 2001, Marty et al. 2001, Eugster et al. 2002, Christen et al. 2005 and others).
Meteorites from the Moon were also found in Antarctica
But what process could launch meteorites from the surface of another planet?
Volcanic eruptions can get pretty violent….

But the thermodynamics of volcanic eruptions puts strict limits on the maximum ejection velocity.
Gene Shoemaker and Don Gault, leading experts on impact processes in the 1970s, declared that the launch of intact rocks from a planet the size of Mars is impossible.
They based their objections on the experimentally determined relation between impact velocity and shock pressure.
But the infamous Martian meteorite 84001…
Shows no sign of shock on launch at all, and never got hotter than 40°C in its travel from Mars to Earth.
The ejection of rock fragments at high speed is also strongly supported by the discovery of the remarkable crater Zunil on Mars, and others like it.

Gratteri (from THEMIS, 545 X 533 km image), 6.9 km diameter

Zunil, 10.1 km diameter
Consider the pressure and density changes that occur near a 1 km diameter asteroid impact at 12.5 km/sec:
Studies like this suggest that the near-surface rocks can be ejected at high speed without serious damage.
The key to high-speed ejection without heavy shock damage is known as “spallation”, and was first observed in the vicinity of buried nuclear explosions.
In underwater explosions, the spall zone is clearly marked by a white disk of cavitating water.

Figure 2.67a. The condensation cloud formed after a shallow underwater explosion. (The "crack" due to the shock wave can be seen on the water surface.)
Impacts are not like nuclear explosions, because they are open from the beginning, but shock waves they create interfere near the surface to create a low pressure zone.

Kamegai, LLNL, 1986
Modern high resolution impact simulations show that the surface remains a low pressure region in both vertical and oblique impacts.

Pierazzo, et al.
The net result is ejection at high speed, but low shock pressure.
The surface ejection velocity falls off as predicted with distance from the impact

From Head et al. 2002
Carol Polansky and Tom Ahrens observed fracture patterns in impacted rocks consistent with expectation from this spall process.
Modern numerical models incorporate fracture during impact simulations and successfully model dynamic fracture formation.
We compute fragmentation using a dynamic tensile fracture model of Grady and Kipp, based on activation of preexisting flaws. It was originally developed for oil shale blasting.
We tested the theory against impact fragmentation of basalt spheres
This theory also agrees pretty well with observed fragment sizes and ejection velocities from impact crater secondary impacts.
Some mysteries still remain: For example, secondary craters on Mercury seem to be considerably larger than their lunar or Martian counterparts.
Ejection of rocks from the surface of nearly airless bodies like Mars or the Moon might work, but could solid rocks be launched from the surface of a planet with an atmosphere, like Earth or Venus?
The very existence of distal ejecta deposits, such as tektites or microtektites on Earth suggest that ejecta from an impact do pierce the atmosphere
Rock fragments are carried through the atmosphere by the expansion of a massive plume of vaporized rock.
This happened when the 24 km diameter Ries impact crater in Germany formed some 15 Myr ago
Meter-size blocks of rock were ejected from the uppermost rock layer
And fell 300 km away, in Switzerland
Speculation: If impacts can eject lightly-damaged rocks from the surface of a planet, could *microbes* be ejected alive?
Mars is pretty desolate right now
But there is abundant evidence of ancient water flow on the surface.
That suggests that Mars was once much warmer and wetter.
Could impacts on Mars have ejected *living* microbes?
Microbes would have to survive a host of hazards
Microbiologist Wayne Nicholson (KSC and U. Florida), I and a long list of collaborators over the past 7 years have performed a series of experiments to test the ability of dormant spores to survive acceleration, reentry and shock, as well as making extensive surveys of the microbial load of candidate launch rocks.
Early setup for ballistics experiments

Heather Glanzberg
Air Rifle
Chronograph
Target
Backstop
In 2004 we arranged a series of impact experiments at the Ames Vertical Gun Range designed to match the conditions of launch from Mars.

Table 1. Estimates of physical parameters for martian meteorite ejection.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Predicted (P) or Measured (M) Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>$3.8 \times 10^6$ m/s$^2$ (P)</td>
<td>3</td>
</tr>
<tr>
<td>Jerk</td>
<td>$6.0 \times 10^9$ m/s$^3$ (P)</td>
<td>3</td>
</tr>
<tr>
<td>Shock</td>
<td>5-55 GPa (P, M)</td>
<td>4-6</td>
</tr>
<tr>
<td>Heating</td>
<td>10-1000°C (P, M)</td>
<td>4-6</td>
</tr>
</tbody>
</table>
We collected spall fragments inoculated with labeled spores of *Bacillus subtilis*–and found a survival fraction of about $10^{-4}$ to $10^{-5}$.

Nicholson, Melosh and Langenhorst, 2009
Planetary Ejecta wanders around the solar system, rather than traveling direct from planet to planet.
And this can take a long time
Spore-forming bacteria are tough

Fig. 4.3 Electronmicrograph of a spore of *B. subtilis* with the inner core containing the DNA surrounded by protective layers, the long axis of the spore is 1.2 μm, the core area 0.25 μm (courtesy of S. Pankratz).
But can dormant microbes really survive for millions of years?

Revival and Identification of Bacterial Spores in 25- to 40-Million-Year-Old Dominican Amber

Raúl J. Cano* and Monica K. Borucki

A bacterial spore was revived, cultured, and identified from the abdominal contents of extinct bees preserved for 25 to 40 million years in buried Dominican amber. Rigorous surface decontamination of the amber and aseptic procedures were used during the recovery of the bacterium. Several lines of evidence indicated that the isolated bacterium was of ancient origin and not an extant contaminant. The characteristic enzymatic, biochemical, and 16S ribosomal DNA profiles indicated that the ancient bacterium is most closely related to extant *Bacillus sphaericus*.

Isolation of a 250 million-year-old halotolerant bacterium from a primary salt crystal

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† Consulting Geologist, Box 87, Anthony, Texas 79821, USA

Bacteria have been found associated with a variety of ancient samples, however few studies are generally accepted due to questions about sample quality and contamination. When Cano and Borucki² isolated a strain of *Bacillus sphaericus* from an extinct bee trapped in 25–30 million-year-old amber, careful sample selection and stringent sterilization techniques were the keys to acceptance. Here we report the isolation and growth of a previously unrecognized spore-forming bacterium (*Bacillus* species, designated 2-9-3) from a brine inclusion within a 250 million-year-old salt crystal from the Permian Salado Formation. Complete gene sequences of the 16S ribosomal DNA show that the organism is part of the lineage of *Bacillus marismortui* and *Virgibacillus pantothenicus*. Delicate crystal structures and sedi-
Some microscopic organisms can tolerate a lot of cosmic radiation, but not much UV, so they have to hide in rocks—this is why we call the modern proposal “Lithopanspermia.”

![A Cosmic Noah’s Ark](image)

Several panspermia scenarios are possible. Molecules of ribonucleic acid (RNA) might have assembled on Mars from smaller compounds, and then traveled to Earth. Or perhaps the RNAs combined to form protein factories similar to present-day ribosomes before making the interplanetary journey. It is also possible that Martian meteorites delivered living cells akin to Deinococcus radiodurans, a modern bacterium that is highly resistant to radiation.
Although it may seem that surviving reentry is difficult,
Meteorites do this all the time.
In the end, it may turn out that Percival Lowell was right about life developing first on Mars, then on Earth, although he would be right for the wrong reason!
There are current concerns that impact ejection might place Mars ejecta on its inner moon Phobos

Last November, 2011, Russia launched the Phobos-Grunt mission, intended to return a 200 gm sample from the 20 km diameter Mars moon moon Phobos.

Phobos-Grunt failed to leave Earth orbit because the Russians used too many off-the-shelf electronic parts in the computer system, but the possibility of a sample return energized the NASA and ESF Planetary Protection groups.
Ejection vel. mag. 4.45 km/
Ejection angle 45 deg
Phobos dir. of motion
Relate Mass / Impact Distribution on Phobos

Mass impacting Phobos as a function of Phobos' relative initial longitude

Collision density on Phobos for each ejection angle

*Assuming the impacting mass is uniformly mixed though a 1 meter deep regolith layer

<table>
<thead>
<tr>
<th>Mass impacting Phobos</th>
<th>Density of collisions on Phobos</th>
<th>30 deg.</th>
<th>45 deg.</th>
<th>60 deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max. impacting mass</strong></td>
<td><strong>Max. collision density</strong></td>
<td>50.077</td>
<td>55.365</td>
<td>53.884</td>
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<tr>
<td></td>
<td><strong>Med. collision density</strong></td>
<td>3.577</td>
<td>2.701</td>
<td>3.499</td>
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<tr>
<td></td>
<td><strong>Avg. over Phobos area</strong></td>
<td>10.306</td>
<td>8.201</td>
<td>7.959</td>
</tr>
<tr>
<td><strong>Med. impacting mass</strong></td>
<td><strong>Max. collision density</strong></td>
<td>2.567</td>
<td>3.052</td>
<td>3.184</td>
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<tr>
<td></td>
<td><strong>Med. collision density</strong></td>
<td>0.183</td>
<td>0.149</td>
<td>0.207</td>
</tr>
<tr>
<td></td>
<td><strong>Avg. over Phobos area</strong></td>
<td>0.528</td>
<td>0.452</td>
<td>0.470</td>
</tr>
</tbody>
</table>
It has been a long journey from meteorites, through fracture mechanics and microbiology in extreme environments, but it leaves us with the final question: Are we all, perhaps, really Martians?