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Impact cratering of soft consolidated astroprotoliths

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***Abstract*—High resolution images sent to Earth by probes orbiting Mercury, Mars and the Moon have allowed us to observe with great detail the morphologies of impact craters.**

A novel hypothesis is presented, supported by experimental evidence, satellite images and new physical models about the processes that take place during granular-granular impacts. The experiments reproduce the morphologies of extraterrestrial impacts and allow us to explain the presence of central peaks, the flat structure, fragmented material inside and around the rims and rays. Our results indicate that these structures are the consequence of granular asteroid and cometary core impacts and that there exist a direct relation between the size of the impactor and the diameter of the crater which is formed by a process of compression of the target and the impactor.

***Keywords*—Granular matter and experiments, Impact craters, Remote sensing.**

***Resumen*— Las imágenes de alta resolución enviadas a la tierra por las naves que están orbitando Mercurio, Marte y la Luna, han permitido observar con mucho detalle las morfologías de los cráteres de impacto.**

Se presenta una nueva hipótesis, soportada por evidencias experimentales, imágenes satelitales y nuevos modelos físicos, acerca de los procesos que ocurren durante los impactos del tipo granular-granular. Los experimentos reproducen las morfologías de los cráteres de impactos extraterrestres y permiten explicar la presencia de picos centrales, la estructura plana, el material fracturado en el interior y alrededor de los bordes y los rayos. Los resultados indican que estas estructuras son el producto de impactos de asteroides y núcleos cometarios granulares y que existe una relación directa entre el tamaño del impactor y el diámetro del cráter y que el cráter se forma por un proceso de compresión del blanco y del impactor.

***Índices*—Cráteres de impacto, experimentos y materia granular, percepción remota.**

I. INTRODUCTION

Several interplanetary probes carries very high resolution cameras capable to take surface images with unprecedented details (Table 1, Fig. 1), such images allow the study of geologic and geophysical processes, occurred and still happening, like impact craters and landslides, among others. Rocky planetary bodies and cores of gas giants, have grown through a continuous process of accretion [1] and collision [2] .

TABLE 1
INTERPLANETARY MISSIONS AND THEIR CAMERAS PERFORMANCE.

MISSION	CAMERA	ORBIT	NOMINAL resolution
Messenger	MDIS (Mercury Dual Imaging System)	Mercury	20 m/pixel
Lunar Reconnaissance Orbiter (LRO)	LROC (Lunar Reconnaissance Orbiter Camera)	Moon	1 m/pixel
Mars Reconnaissance Orbiter (MRO)	HiRISE (High Resolution Imaging Science Experiment	Mars	1 m/pixel
Dawn	FC (Framing Camera)	Vesta	25 m/pixel

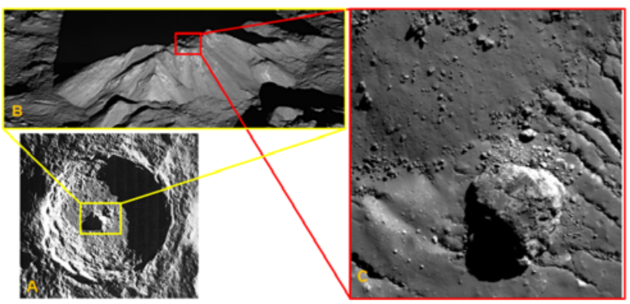

Fig. 1. (A) Tycho crater on the Moon with a prominent central peak. (B) Medium resolution image of the central mountain. (C) Large boulders sitting on the top of the mountain. In this LROC image, the resolution is 0.5 m per pixel. (http://www.nasa.gov/images/content/565812main_tycho_full_full.jpg).

During this process, millions of objects, many of them with diameters greater than several km, wandered chaotically in the plane of the solar nebula, impacting each other. Some of them increased their mass, forming planetesimals and, successively, protoplanets and then planets. Asteroids are all those objects that never coalesced to form larger bodies, and can be considered the rocky planets precursors [3].

Every rocky body in the Solar System shows a large quantity of impact craters with sizes from mm to several hundred km across. Depending on the geologic, tectonic, volcanic, weathering, biologic and erosive processes, typical of each planet or satellite, most of those ancient craters are completely erased from the surface, as occurred on Venus and the Earth, but most of them are well preserved on Mars, Mercury and the Moon.

The rate of impacts has diminished during the last 4 billion years, most of the asteroids are, now, located in well defined areas of the Solar System [4], but there are, also, several groups intercepting planetary orbits, including the Earth. Most of those intercepting bodies are small (several meters diameter) and only a few of them are in the range of km diameter.

Understanding impact crater processes are equivalent to understand the geologic [5] and biologic [6] history of the planets and allows to create hazard maps and mitigation of possible damages.

II. GRANULAR STRUCTURE OF ASTEROIDS

Any object formed by the accumulation of dust and rocks has a granular structure, in which the forces holding together its particles are basically Van der Waals and gravity [7]. Objects grown up to diameters less than 200 km, are very porous and therefore little cohesive, because the lithostatic pressure is too low to initiate metamorphic processes, so they can be considered as having a granular structure (rubble piles or astroprotoliths). Objects with diameters in the range from 200 to 500 km, are only partially differentiated, having some high cohesive and low porosity parts (solids), and other parts maintaining their granular structure, all mixed together. Only big asteroids, dwarf planets, large satellites and planets, show a fully differentiated structure with a granular high cohesive surface, viscous molten intermediate zone and a solid core.

During the first billion years, or even much more [8] after the Solar System formation, due to the frequency of impacts, even objects with diameters up to hundreds of km, had no chance to start or maintain differentiation or metamorphic processes, so they did not lose their granular structure. These objects can be though as the first generation impactors and are the culprits of most of the craters and basins observed today on the surface of Mercury, Mars, the Moon and large satellites of giant gas planets.

Most of the actual asteroids in the Solar System are the remnants of the breakdown of planetesimals, planets and satellites occurred during that epoch. Largest bodies survived and continued the differentiation process, intermediate ones; loose some of their mass and smaller objects, re-accreted after a complete disruption. As a result, asteroids can be grouped into several families, some of which are, now, recognized as highly porous or granular (rubble piles) objects like 253 Mathilde [9].

III. GRANULAR IMPACT BEHAVIOUR

Granular matter behave like a solid, a liquid, a gas or a complex combination of them, depending on several variables like particle morphology, interstitial fluids, environment characteristics, etc.

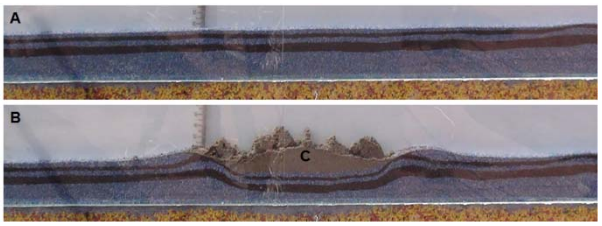

Fig. 2. Bi-dimensional impact experiment results. (A) Target stratigraphy before impact. (B) Target stratigraphy after impact. (C) Impactor after the collision.

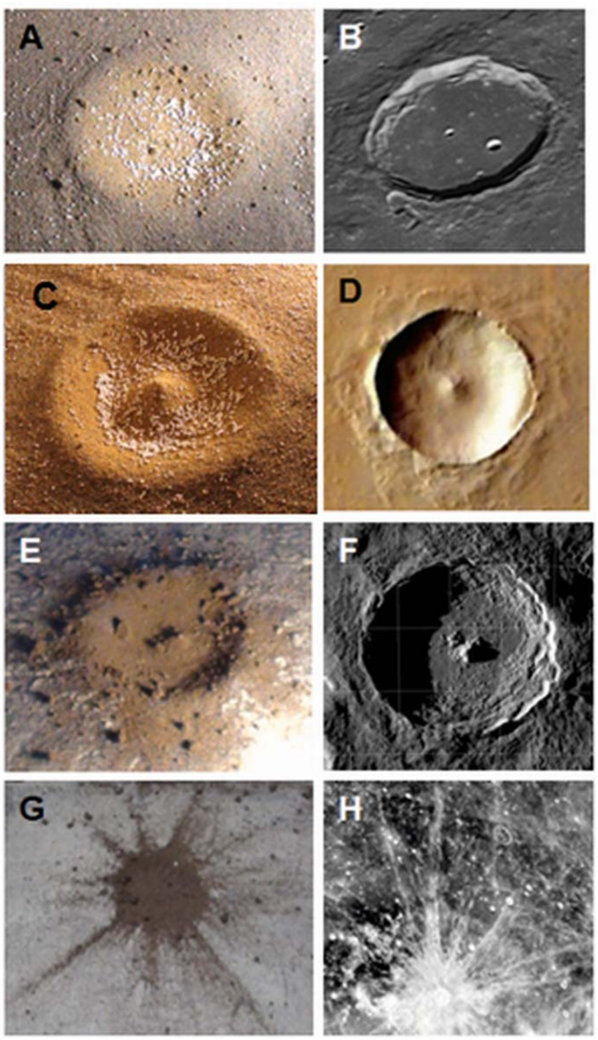

Fig. 3. Comparison between experimental craters and craters on the Moon and Mars surface. (A): Experimental flat bottom crater. (B): Marius crater (flat bottom) on the Moon. (C): Experimental central dome crater. (D): Unnamed central dome crater on Mars. (E): Experimental central peak crater. (F): Tycho crater (central peak) on the Moon. (G): Experimental ray crater. (H): Kepler crater and rays on the Moon.

A granular body impacting another granular object, produce a crater whose morphology is very similar to those observed everywhere in the Solar System. However, the process of crater formation depends on the behavior of the colliding objects, so a granular-granular collision is different from a solid-solid or solid-granular one.

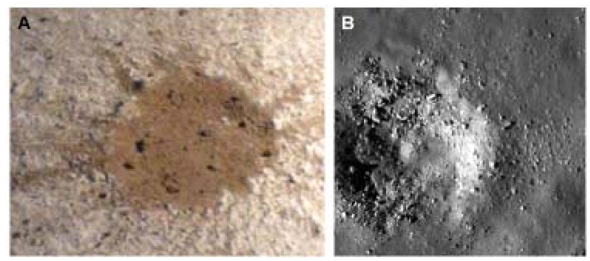

Fig 4. (A) Debris in the interior of an experimental crater. (B) Debris in the interior of a very fresh crater on the Moon (NASA-LROC).

Until now, most of the experiments, theoretical models and computer simulations are done thinking that the impactor is a solid [10]. Due to the granular structure of asteroids and planetary surfaces covered by fine and large regolith, there is the need to design experiments and create physical models and computer simulations focused on the granular matter behavior. Our group is the first developing experiments and theoretical models aimed to explain impact processes involving projectiles and targets made of granular material [11].

A process, we called “Dynamic Compression and Confinement” (DyC&C), is responsible of the formation of a crater when a granular-granular collision occurs. The first step is the compression of the projectile and its partial destruction. Due to the low efficiency of the transmission of forces (hypersonic comminution), typical of granular behavior, the target is slightly compressed. The upper part of the projectile is not fully destroyed and produces an ultra-fast avalanche and, the momentum is transferred horizontally to the target, opening a crater. The energy not used by compression, drives parts of the impactor upward forming the ejecta.

To visualize this phenomenon, we performed 2D granular impact experiments, where a porous disc made of sand, was slid down a thin channel from a 7 m height, impacting on a bed of granular material. The analysis of the resulting stratigraphy, after the impact, with the help of high speed videos, showed the effect of the DyC&C (Fig. 2).

3D experiments performed (simulating porous asteroids) by means of spherical balls of sand impacting on a granular bed, reproduced several crater morphologies very similar to those observed on the Moon and Mars: flat bottom, complex central peak, central dome craters and ray craters (Fig. 3). Experiments show that most of the ejecta and fragments remaining inside the crater belong to the projectile (Fig. 4), the rays are the product of large fragments

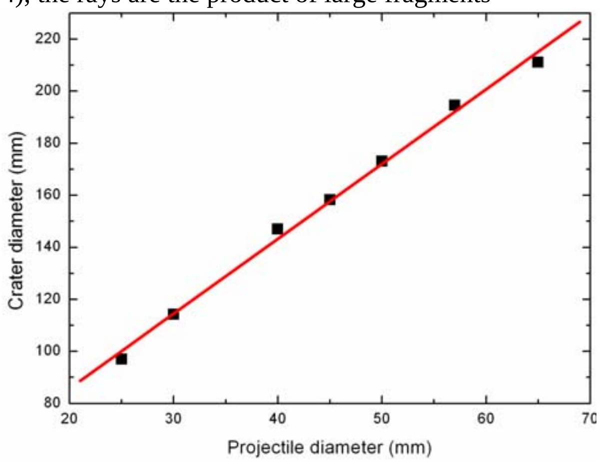

Fig. 5. Relationship between projectile diameter and the corresponding crater diameter.

of the impactor ejected from the crater interior. Our results also show that there is a direct relationship between the projectile diameter and the resulting crater diameter (Fig. 5), implying that large lunar craters were made by large granular impactors.

IV. CONCLUSIONS

Our experiments are capable of producing impact craters with different morphologies, when they are compared to those observed on the surface of rocky bodies in the Solar System, they are very similar. Due to the granular structure of the first generation of objects formed in the Solar nebula, more than 4 billion years ago, their chaotic orbits and to their successive fragmentation, most of the impact craters were made by granular asteroids, whose dimensions have a linear relationship with the projectile diameter. A granular-granular impact process is a sequence of compression and lateral transfer of momentum due to the Dynamic Compression and Confinement physical model.

V. AKNOWLEDGMENTS

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