IL NUOVO CIMENTO **44 C** (2021) 161
DOI 10.1393/ncc/i2021-21161-y

COMMUNICATIONS: SIF Congress 2020

Analysis of lunar craters: A PLS path among impact physics, craterization simulations and image processing

M. D'ELIA(1), D. LICCHELLI(2), V. OROFINO(1), F. STRAFELLA(1),
M. L. DE GIORGI(1) and A. VENTURA(1)

(1) *Mathematics and Physics Department "Ennio De Giorgi", University of Salento Lecce, Italy*
(2) *R.P. Feynman Observatory, CBA Center for Backyard Astrophysics Gagliano del Capo, Lecce, Italy*

received 15 January 2021

Summary. — This contribution concerns the training course that the Astrophysics Group of the University of Salento proposed to the students of the Piano Lauree Scientifiche for the school year 2019–2020. Since the first edition of the Piano Lauree Scientifiche - Fisica of the University of Salento, the proposal of the Astrophysics Laboratory has been varied and every year different topics have been addressed, developing new methodologies for a more attractive teaching and a better education guidance. Arousing great interest from students, this year the proposal of the Astrophysics Group was dedicated to Planetology with a direct laboratory experience focused on the simulation and analysis of impact craters. After an introduction on the minor bodies of the Solar System and on the impact crater physics, the students digitally processed images of the Moon's surface with a dedicated software, obtained the necessary information for the subsequent calculation of the involved physical parameters, and finally processed the results, comparing them with those reported in the literature.

1. – Introduction

The Piano Lauree Scientifiche (PLS) is an Italian national project with the aim to increase the number of motivated and capable students enrolling in University STEM courses. In particular, the Department of Mathematics and Physics "Ennio De Giorgi" of the University of Salento offers different educational paths for the PLS in Physics, giving the opportunity for high school students to explore scientific topics, problems and procedures concerning Astrophysics, Modern Physics, Classical Physics, Environmental Physics, Physics for Cultural Heritage and Optical Physics. The purpose is to develop students' self-assessment skills, to consolidate the knowledge necessary for access to University scientific courses, and to provide an important reference to post-graduate career opportunities. Moreover, thanks to the joint design and implementation of laboratory experiences by high school and university teachers, the students discuss issues and ideas in the scientific field.

Since the first edition of PLS, the proposal for the students of the Astrophysics Laboratory has been varied and every year an attempt has been made to present different topics. After the ones concerning Exoplanets transits, Radiometeor Analysis, Spectroscopy applied to stars, comets and other natural and artificial sources for which students showed great interest, this year the laboratory was dedicated to the origins of the Solar System with the application section focused on the simulation and analysis of impact craters with observational checks and measurements on lunar craters.

After an introductory lecture on the formation of the Solar System, from the protoplanetary disk to the planets, we moved on to talk about satellites of planets, dwarf planets, asteroids, transneptunian objects, comets, meteoroids, and interplanetary dust, with particular attention to scientific activities concerning minor bodies in which the Astrophysics Group was directly involved (in particular, the Rosetta ESA mission and the PRISMA Italian Project).

2. – Impact crater physics and cratering processes

The laboratory activity of the PLS Astrophysics path was preceded by a theoretical introduction on the definitions, the classification of impact craters and how the craters are formed [1]. Simple theoretical considerations were also made on the energy released in the impact, and on the work that is carried out against gravity to raise the mass of the material present in the hole by a certain height, in order to investigate the theoretical relationship between the projectile kinetic energy and the diameter of the formed crater. The positive energy E released in the impact is equal to the absolute value $|L|$ of the work performed against gravity to raise the mass of the material previously present in the hole to a height $h_0 = R$,

$$E = |L| = Mgh_0 = MgR = \frac{2}{3}\pi\rho g R^4, \tag{1}$$

where g is the gravity acceleration, while M and ρ are, respectively, the mass and the density of the ejected material.

The energy released (E) in the impact is equal to the kinetic energy (K) dissipated in the impact, therefore

$$K = \frac{2}{3}\pi\rho g R^4 = \frac{2}{3}\pi\rho g \left(\frac{D}{2}\right)^4 = f_0 \rho g D^4, \tag{2}$$

where f_0 is the form factor given by $f_0 = \frac{1}{24}\pi$ for a hemisphere with D diameter, and $f_0 = 1$ for a cube with D side.

Therefore, the kinetic energy of the projectile is related to the diameter of the resultant crater through the simple relationship

$$K = A \cdot D^B, \tag{3}$$

with $A = f_0\rho g$ and $B = 4$. If D is expressed in km and K in joules, then $A = 3.5 \times 10^{15}$ for the Earth, while $A = 5.7 \times 10^{14}$ for the Moon.

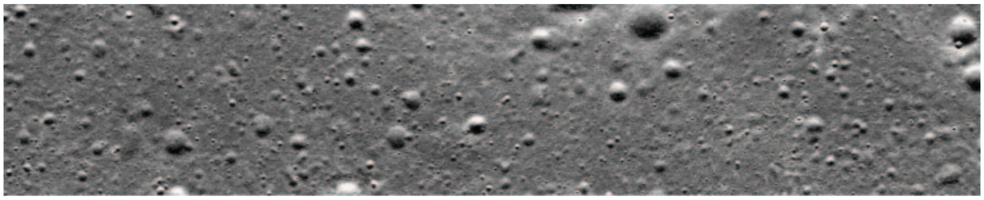

Fig. 1. – High resolution image (55190 × 7860 pixels in size) of a densely cratered area of the Moon taken by the NASA lunar orbiter LRO (Apollo 11 Site, LROC Observation M150361817R, Arizona State University).

For the lunar crater, a similar law is reported in literature [2] but with $A = 2.7 \times 10^{17}$ and $B = 3.045$, while from the Potter and Kring simulations [3] it is possible to obtain a more reliable relationship adopting the values $A = 1.3 \times 10^{16}$ and $B = 3.289$.

After theoretical considerations, we specifically examined several numerical simulations based on impact craterization processes [3], where impacts of asteroids with the Earth and the Moon are simulated. In particular, for our satellite, these authors have taken into consideration asteroids of various density, various diameter (D'), and velocity between 10 and 35 km/s obtaining the D diameter and d depth of resulting craters. Their resultant relationships are

$$d = (0.24 \pm 0.02)D, \tag{4}$$

$$K = (1.3 \times 10^{16})D^{3.289}, \tag{5}$$

where $D = (25 \pm 5)D'$, and K is expressed in joules if D is in km.

High-resolution images taken by NASA lunar spacecrafts showing simple craters (with their distinctive hemispherical shape), complex craters (with a typical morphology characterized by terraces and a central peak), and impact basins (often degraded structures larger than 300 kilometers in diameter) were analyzed in details. The students also had the opportunity to view various simulations of crater formation, made available by [3] at the Lunar and Planetary Institute website, by changing some parameters of the impactor (such as its final velocity and its size and/or density).

3. – Educational/laboratory experience

Moving on to the direct teaching experience, a high resolution image (up to 50 cm per pixel) of the lunar surface centered on the Apollo 11 landing site (see fig. 1) was provided to the students. As we always do for all PLS laboratories, the students were divided into groups. Each group selected about 15 craters of different sizes, and analyzed them with ImageJ software (a free software downloadable online [4]). Of the selected craters, the students determined the diameter, calculated the depth and verified the Potter and Kring proportionality law (eq. (4)). Then, choosing one of the selected craters, they also determined the diameter and the final speed of the impacting body, and the released energy calculated by using eq. (5).

We also prepared a video tutorial on the use of the ImageJ Software which allowed the students to have a very useful guide and a step-by-step support in the image analysis activity.

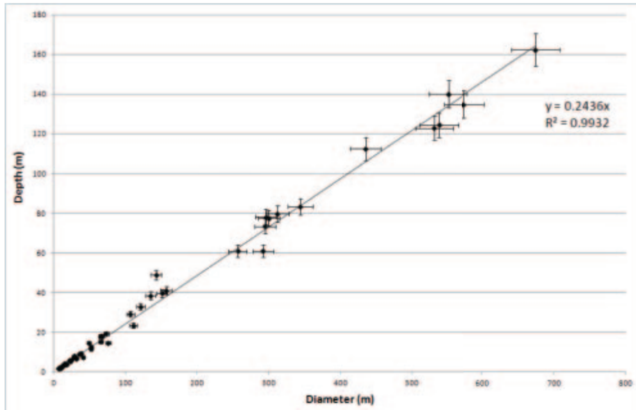

Fig. 2. – Plot of the depth (d) *vs.* the diameter (D) of the 50 craters analyzed by all groups of students.

Each group analyzed a set of craters chosen by them, and recorded the obtained data in a spreadsheet inserting, for each crater, its coordinates, the diameter D determined using ImageJ software, and the value of the depth d calculated by simple trigonometric formulas using the measured length of the rim shadow (also obtained by means of ImageJ), given the azimuth of the Sun and its height over the horizon.

The students also calculated the error bar for each final value, observing that the uncertainty is negligible for small craters and increases for the larger ones. This is due to the fact that for large craters it is difficult to correctly define the edge on the image of the Moon's surface.

4. – Results and conclusions

At the end of the course, each group of students submitted a final report on their findings as a learning portfolio to demonstrate the development of their knowledge and skills over time.

Even with the limitations related to the error calculation described above, in fig. 2 an excellent correlation and a very good agreement between the obtained proportionality coefficient (0.24) and the one derived by [3] (eq. (4)) were achieved. Therefore, combining the data of all groups and analyzing the resulting graph, the collective verification of the proportionality law had a positive outcome.

This PLS path aroused great interest from students, who became aware of the fact that the impact crater analysis is an interesting scientific topic and has important implications for a safe long term human exploration of the Moon and Mars.

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