My Summer Internship at the NASA Jet Propulsion Laboratory:
Assessing the Age of an Asteroid’s Surface with Data from
the International Rosetta Mission

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**Abstract:**

Rosetta is an international mission led by the European Space Agency (ESA) with key support and instrumentation from the National Aeronautics and Space Administration (NASA). Rosetta is currently on a ten-year mission to catch comet 67P/Churyumov-Gerasimenko (C-G); throughout its voyage, the spacecraft has performed flybys of two main belt asteroids (MBA): Steins and Lutetia. Data on the physical, chemical, and geological properties of these asteroids are currently being processed and analyzed. Accurate interpretation of such data is fundamental in the success of Rosetta’s mission and overall objectives. Post-flyby data analyses strive to correlate the size, shape, volume, and rotational rate of Lutetia, in addition to interpreting its multi-color imagining, albedo, and spectral mapping. Although advancements in science have contributed to the examination of celestial bodies, methods to analyze asteroids remain largely empirical, not semi-empirical, nor *ab initio*. This study aims to interpret and document the scientific methods currently utilized in the characterization of asteroid (21) Lutetia in order to render these processes and methods accessible to the public. Examples include a standardized technique for assessing the age of an asteroid surface, complete with clickable reference maps, methodology of grouping surface characteristics together, and a standardized power law equation for the age. Other examples include determining the density of an object. Context for what both density and age mean is a bi-product of this study. Results of the study will aid in the development of pedagogical material on asteroids for public use, and in creation of an academic database for selected targets that might be used as a reference.

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1. Background

Asteroids are metallic rocky bodies that orbit the Sun but are too small to be classified as planets. Known as “minor planets,” tens of thousands of asteroids congregate in the main asteroid belt: a vast, doughnut-shaped ring located between the orbits of Mars and Jupiter from approximately 2 to 4 AU (300 million to 600 million kilometers). Asteroids are thought to be primordial material prevented by Jupiter’s strong gravitational field from accreting into a planet-sized body. It is estimated that the total mass of all asteroids would comprise a body approximately 1,500 kilometers (930 miles) in diameter – less than half the size of the moon.

Asteroids are physically, chemically, and geologically diverse. These bodies vary in size and shape, as shown in Figure 1, in addition to being composed of different minerals and other materials. Due to the diversity of their composition, asteroids are categorized into different taxonomies including the following four groups: C-type, S-type, M-type and E-type asteroids. Each of those taxonomies is determined by analyzing the surface’s albedo, which is the magnitude of light reflectivity of the surface, which serves as an indicator of the asteroid’s possible composition. Asteroids with very dark albedo (0.03-0.09), as an example, are thought to have a similar composition as the Sun, depleted in hydrogen, helium, and other volatiles. These asteroids are classified as C-type, or carbonaceous, and make up more than 75 percent of known asteroids.

Earth has been exposed, since its formation, to asteroid impacts that vary in magnitude and size. Evidence of such interactions is found on craters and other geological trends on Earth’s surface, most of which can be observed and measured. These events have largely influenced the evolution of our biosphere and ecosystem. The most notorious asteroid impact, perhaps, is the one that occurred about 65 millions years ago causing the extinction of dinosaurs and other marine and land species. Due to the dynamic nature of these celestial bodies, as well as their constant interaction with our planet, the analysis of asteroids is essential to understand and possibly avoid such impacts. In addition, asteroids can provide evidence of the early stages of the solar system’s formation process, in addition to being rich supplies of minerals, which can even be used as alternative sources of energy on Earth or possibly for future space exploration missions.

2. Introduction

The understanding of asteroids has been derived from three main sources: Earth-based remote sensing, laboratory analysis of meteorites, and space exploration missions. Unmanned missions to asteroids have allowed conceptualizing the nature of asteroids by providing multi-
color images (see Figure 2), albedo, and spectral mapping. Although advancements in science have contributed to the examination of such data, methods to analyze asteroids remain largely empirical. This study aims to interpret and document the scientific methods currently utilized in the characterization of asteroid ages in order to render these processes and methods accessible to the public. Results of the study will aid in the development of pedagogical material on asteroids for public use, and in creation of an academic database for selected targets that might be used as a reference. This paper will present and explain the scientific process utilized in assessing the collisional age of an asteroid’s surface, which will be used to assist U.S. Rosetta’s development of activities for outreach purposes.

3. Procedure

The objective of this procedure is to create the Model Production Function (MPF) from which the mean collisional age of an asteroid’s surface can directly be approximated. To do it we must (1) identify and characterize the crater population on the surface; (2) analyze the crater distribution; (3) the impactor flux must be derived, and (4) converted to a functional form in a single variable using a scaling law (SL). (5) The impactor flux function is then integrated over all crater sizes, after accounting for ‘erasing’ and material properties of each target, thus obtaining its MPF. The MPF obtained will then be fitted into the crater population graph created in (2) in order to predict the surface’s collisional age.

(1) Crater Population and (2) Crater Distribution

By doing a visual inspection of the asteroid’s pictures obtained from the spacecraft, we will identify its crater population. Craters will be categorized as bona fide craters or crater-like features depending on the sharpness of its edges. Bona fide craters are those with well-defined edges that can be clearly identified. The rest, therefore, will be classified as a crater-like feature. By performing a visual analysis, we must then determine which of those crater-like features can be considered as actual craters, and therefore, consider as such for the rest of our procedure.

Once the surface has been visually inspected, the result will be a table containing the crater’s overall number and diameter. Once the table is completed, the user must plot a “Crater Diameter vs. Cumulative Number of Craters per km$^2$” graph (as shown in Figure 4).

When performing this step (Marchi et al., 2010), asteroid (2867) Steins presented a total of 71 crater-like features and a total of 18 bona fide craters, ranging from .2 to 2.1 km in diameter. The effective area over which counts have been performed is 23.7 km$^2$. Such count was based on the visual inspection of three wide angle camera (WAC) images taken by
the Rosetta spacecraft. One of such pictures is shown in Figure 3. The diameter of Stein’s craters were also measured, and the value for the Cumulative Number of Craters per km² was obtained by dividing the cumulative number of craters of same diameter, by the total surface area of over which craters were found (27.3 km²). The “Crater Diameter vs. Cumulative Number of Craters per km²” graph for Steins is shown in Figure 4.

**FIG. 4. Cumulative distribution of all crater-like features and bona fide craters.** The resulting distribution shows a remarkable paucity of small craters when compared to the distribution of all detected crater-like features. Image credit: See Marchi et al. 2010.

(3) **Impactor Flux**

Next we must calculate the impactor flux, which is expressed in terms of a differential distribution, which represents the number of incoming bodies per unit of impactor size \( d \), impact velocity \( v \) and per unit time. The flux can be written as:

\[
\phi(d, v) = h(d) f(v) \quad (I)
\]

where,

\( h(d) \) = impactor differential size distribution, and

\( f(v) \) = distribution of impact velocity normalized to \( \int f(v)dv = 1 \).

The impactor size distribution is derived using a model of the average size distribution of the main belt derived by Bottke [2005]. The estimated number of impactors at the asteroid is then obtained by multiplying the average size distribution (calculated by previous scientific observations) times the intrinsic probability of collision with asteroid, \( P_i \). The latter is evaluated by taking into account the observed orbital distribution of main belt asteroids. The impact velocity distribution \( f(v) \) has been evaluated considering the population of main belt asteroids that presently intersect the asteroid’s orbit.
(4) Scaling Law

The impactor flux is then converted into a cumulative crater distribution of model production function, MPF, using a scaling law (SL). The purpose of a scaling law is to find a relationship between the diameter of the impactor and the diameter of the crater such object will produce on the asteroid’s surface. Because of this the SL utilized will depend on the physical characteristics of the asteroid, as well as the rate and velocity of the impacts.

For Steins an unfractured silicate rock was assumed and using the relevant specific energy for disruption, \( Q_d = 1 - 2 \times 10^7 \text{erg/g} \), we derive that an impact at an average modulus velocity of 5.7 km/s with a body having size \( d_{cd} = 0.20 – 0.25 \text{km} \) would be sufficient for catastrophic disruption. Moreover, for an unfractured rock with surface gravity \( g \) and density \( p \), the transition from strength to gravity cratering occurs at a crater diameter of \( \sim 0.8Y/gp \), which exceeds the size of the Ruby crater, expect the cases of unreasonably low \( Y \) values for a silicate body. Therefore, using HSL the strength regime applies for Steins. Under these conditions, we obtain that a 2 km crater is produced by an impactor having \( d \sim d_{cd} \). In conclusion, from previous reasoning, we limit our investigations to HSL for cohesive soils (blue dotted and dashed curves in fig 6), and test the effects of different tensile strength. HSL equations read, for cohesive soils and water, respectively:

\[
D = k_d \left( \frac{Y}{p \sqrt{\mu}} \right)^{\mu/2} \left( \frac{p}{\delta} \right)^{\nu} \tag{2}
\]

\[
D = k_d \left( \frac{gd}{2 \sqrt{\mu}} \right)^{-\mu/(2+\mu)} \left( \frac{p}{\delta} \right)^{\nu} \tag{3}
\]

where,

- \( D \) = crater diameter
- \( v_\perp \) = normal component of the impact velocity
- \( \delta \) = impactor density
- \( k, \mu, \nu \) = depend on the material and are derived from experiments

For Steins, the Nolan cratering scaling law (NSL) was also utilized. The process introduces a term called “fracture regime,” which basically claims that small craters are formed in the classical way, with their size being controlled by the local strength. In large craters, on the other hand, the shock wave propagates ahead of the excavation flow, and therefore the material is totally fractured prior to its removal. If the amount of excavated material is large enough, the size of the resulting crater is controlled by the gravity. NSL can be arranged in the following manner:

**FIG. 5.** Stein’s cumulative impactor size distribution (left panel) and impact velocity distribution (right panel) used in the present work. For a comparison, the lunar impact distributions are also shown in red. Image credit: See Marchi et al. 2010.

**FIG. 6.** Relationship between impactor diameter (d) and crater diameter (D) according to the scaling laws discussed in this work. See Marchi et al. 2010.
Using this, and plotting a “d vs. D” or “impactor diameter (d) vs. crater diameter (D)” graph, we are able to transpose the impactor flux from step 3, $\phi(d, v)$, into a function depending only on one variable D. Thus, the final product of step 4 is the equation $\phi(D)$ flux as a function of (D) alone not flux as a function of d and v.

(5) Modeling Production Function

The model production function (MPF) is the differential distribution $\phi(D)$ of the number of craters with respect to their diameters expressed per unit time and surface area. The MPF can be obtained by:

$$MPF(D) = \int_D^\infty \phi(D') dD'$$ \hspace{1cm} (5)

This equation implicitly assumes that all craters accumulate over time without interfering with previously formed craters (no crater erasing) and that the flux is constant over time. The latter assumption is valid in this case, according to lunar chronology, for ages less than 3.7 billion years old. The former, however, must be fixed by including an additional component to the equation, thus written in the following manner:

$$MPF(D, t) = \int_D^\infty \phi(D', t) \epsilon(D', t) dD'$$ \hspace{1cm} (6)

where,

$$\epsilon(D, t) = \text{the ratio of the final number of craters, erasing included, to the total number.}$$

The mentioned erasing process depends on several parameters, as the regolith jolting and superposition of craters on the surface.

By utilizing the previous equation, we will obtain a function for the MPF in terms of the crater diameter, D, and the time, t, through which the surface was exposed to being hit by other asteroids and celestial bodies. Using the “Crater Diameter vs. Cumulative Number of Craters per km$^2$” graph created in steps (1) and (2), we will be able to approximate the collisional age of the surface by fitting the MPF into this graph. The MPF that best fits the graph will be an indicator of the mean collisional range of the asteroid’s surface, which, in the case of Steins is of about 150 to 500 million years old.
FIG. 7. Left panel: Stein’s age estimates obtained with the MPF and no crater erasing. The best fits have been performed considering only craters for $D > 0.6$ km. Right panel: Steins’ age estimates obtained with the MPF and crater erasing. The best fits for small diameters is also shown, possibly indicating the time of the formation of the Ruby crater (30 to 70 million years ago). See Marchi et al. 2010.

4. Conclusions

The process developed in the previous section was obtained as a result of this research. This five-step process will be used as a reference to develop activities for outreach purposes by the United States portion of the International Rosetta Mission (U.S. Rosetta). As a result of this research, we are in the process of developing an activity to guide K-12 students about the science of determining the age of an asteroid’s surface. The process described above would serve as the basis to implement such activities, which intend to introduce students to concepts of STEM fields such as astrophysics and cosmology. In addition, the activity strives to guide students while they discover the scientific process utilized in assessing the age of an asteroid, thus making them aware of the challenges faced by scientists and engineers.

In addition, we have proposed the development of a supporting activity, which strives to give a historical perspective to the age of an asteroid. To achieve this, we created a timeline with the 50 most significant events since the creation of the solar system. Each event contains a description that provides a general idea of what was happening in different planets, in addition to the constant changes in biosphere of planet Earth. The activity itself consists of having the user (students) drag and place the asteroid, according to its age, in the right location of the solar system’s timeline. By doing this, students will now be able to associate the age of an asteroid with a specific event happening in our planet or any other object in the solar system.

The main purpose of this project was to support the outreach efforts of the U.S. Rosetta team, by developing a procedure on assessing the age of an asteroid surface. The project strived to make these scientific processes understandable and available to the general public, especially students, as a way to introduce them to these relatively new scientific fields and consider STEM as a prospective career.

5. My Internship Experience

As a result of my internship, I have been able to apply and enhance my skills in both science and mathematics. I used advanced math skills to find the functional dependence of properties, like impactor and crater diameters, in order to successfully complete the steps of the procedure. In addition, I learned how to interpret line fits to data with limited view on the data points; as well as apply my scientific and observational skills to analyze an interplanetary surface for geological features that I had no previous experience identifying. In order to successfully complete my project, I also utilized my knowledge of different chemical elements, especially those that are important in planetary science, including: oxygen, carbon, hydrogen, sulfur, aluminum, iron, silicon, and magnesium. Besides applying my math and science skills, I had to develop my knowledge of the Earth’s geologic history, and other planets in the solar system like Mars and Jupiter. I learned concepts on the formation of the solar system and even on stellar astronomy.
This internship, besides improving my academic development, it also allowed me to apply a variety of interpersonal skills. I had to apply my communication skills to effectively and clearly transmit my ideas to my mentors, as well as to articulate the complex scientific concepts utilized in the procedure. Besides that, I enhanced my time-management skills, as I had to arrange and organize my schedule to attend meetings and seminars, as well as to invest time on my research. In addition to that, I had to organize and lead meetings where I would discuss the advancements of my project, as well as encourage discussion on the activities developed as the result of this research. Tasks included: convening a team for a meeting, evaluating the agenda for and content of the meeting, running a meeting with people of different backgrounds, et cetera.

As part of my extracurricular involvement as a JPL intern, I had the opportunity of serving as mentor, in addition to being a volunteer for a NASA-sponsored festival. I practice skills involved with interfacing with the public in an engaging way, in order to render my scientific research understandable and compelling, as well as to make students aware of the different opportunities to get involved with NASA. The internship allowed me to look into different STEM fields, like astrophysics and astrobiology. By exploring different fields, I will be able to make a good decision on my future career goals. My internship gave me a good sense of the technical and personal skills needed to be successful in life after graduation, thus being a well-rounded experience.

6. Acknowledgements
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7. References


