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The lunar crater chronology and the early evolution of the solar system

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Abstract

Craters represent one of the most spectacular surface features of solid bodies of the solar system. They are ubiquitously present in the solar system, from the surface of the innermost planet Mercury, to the outermost natural satellites of gaseous giant planets. Despite the diffuse presence of impact craters in the solar system, the most important astronomical body for cratering studies is certainly represented by our natural satellite, the Moon. This is partially due to the lunar exploration era which allowed to entirely map the lunar surface and to bring back on Earth rock samples for detailed mineralogical analysis. In addition to this, the Moon has an unique history which makes or satellite a sort of *rosetta stone* to unveil the past evolution of the solar system.

One of the most important outcome of the lunar exploration era was the precise radiometric age estimate for several lunar terrains. Radiometric ages together with cratering studies allowed the development of chronology models for the Moon and the terrestrial planets.

Recently, thanks to a fleet of new space missions (e.g. Messenger to Mercury, and Selene to the Moon) this field of research entered a new exciting phase, where accurate age estimate provide means for detailed geological studies.

This work aims to present the latest results in the field of lunar crater chronology, as well as to give an overview on how the early chronology of the Moon and terrestrial planets may retain the footprints of the formation of the solar system.

1. The inner solar system crater chronology

It is important to underline that any chronological assessment from remote analysis (i.e. not based on radiogenic isotope analysis of rock samples) is intimately connected to studies of the impact history of the inner solar system. Such studies have been ranked at the highest level of priority among several science concepts identified for mid- and long-term exploration of the Moon (e.g. [1]). The crater-based chronology is therefore a fundamental tool of investigation for planetary scientists, since it provides the only means presently available for precise age determination of extraterrestrial bodies (planets, asteroids etc), where radiometric calibration through laboratory analysis of rock samples is not yet possible.

Planetary crater chronology was developed in the 60's, with the onset of the space exploration era. Detailed studies and refined analysis were pursed during the period of the cold-war, taking advantage of USA-USSR competition for lunar exploration (over 50 spacecraft were sent to the Moon from 1959 to 1976). An enormous amount of data were gathered and processed in order to obtain the *reference chronology* for the inner solar system [2, 3, 4, 5]. The reference chronology was derived using an experimental approach. It develops a chronology of a reference body for which two measurable quantities are available: absolute ages and surface density of craters for selected areas. The Moon is the only body of the solar system for which both of these can be determined, and therefore has became the *standard clock*. Then, on the basis of models predicting the impactor flux ratio between the Moon and another generic body, it is possible to estimate the age of the latter. In this way, the chronologies for Mars and Mercury have been derived.

On the other side, the understanding of the formation and evolution of the solar system and the physics of cratering processes has dramatically improved in the last 15 years. In addition, recent space missions to the Moon (Clementine 1994, SMART-1 2003, SELENE 2007, LRO 2009), have provided new high quality lunar imaging. Despite all of these improvements, the lunar chronology has remained inexplicably detached for decades by these increasing knowledge of the formation of the solar system. Only in recent years, new schemes were proposed.

Thanks to the aforementioned recent improvements of our understanding of the dynamics of the inner solar system, some weak points in the standard lunar chronology have been identified [6]. In particular, it has been shown that the main assumption (namely, the fixed crater size distribution) involved in the reference chronology may not be valid. This result has important implications for the evolution of the Moon, and could help to constrain with more precision its early stages. Moreover, the present best prediction of the size-frequency distribution of near-Earth objects (NEOs) matches the observed lunar cratering for ages younger than 3.7 billion years, and evidences for an increase in the impact rate respect to the average flux in very recent times (< 400 Myr) have been found [6]. The overall scenario which is emerging is that the observed lunar cratering may be reconciled with state-of-the-art solar system dynamical model (the so-called *Nice model*, [7]). Nevertheless, a lot of work still has to be done to develop a new, more precise, lunar chronology. The same is also true for the chronology of Mars and Mercury, which suffer from both the uncertainties mentioned above and from biases introduced by the extrapolation of the lunar chronology [6, 8].

2 New trends of investigations

In order to accomplish the aforementioned goals, a multidisciplinary approach is essential. Here we limit to outline some of the most important issues that will be likely the core of future investigations.

A primary task is to focus on the evolution of the impactor population, which is closely related to the evolution of the main belt asteroids and the formation of the gaseous giant planets. Another aspect of interest is the formation of asteroid families, which may give rise to sporadic increases in the impactor flux rate onto terrestrial planets. These studies should be supported by new analysis of planetary terrains, devoted to a better characterization of the local geology and the cratering record. In particular, these aspects could be addressed to constrain the pre-Nectarian (3.9-4.4 Gyr) and the Copernican (from 1.1 Gyr to present) periods, which are both poorly known epochs of the Earth-Moon system history. These investigations will be used to obtain a robust prediction of the crater size frequency distribution on the Moon (the so-called Model Production Function -MPF- [6]), valid since the lunar formation (4.4 Ga ago) to present. Notice that these investigations will also have a positive feedback on the dynamical models for the formation of the solar system, since the observed cratering record on the oldest terrains on terrestrial planets might provide snapshots of the mobility of the small bodies in the solar system; and therefore trace the early evolution of the giant planets. In this respect, best examples are offered by the Moon and Mercury since they retain a large portion of their primordial crusts.

3. Summary and Conclusions

Here we present the potentiality of the MPF-based chronology, by describing new results concerning the lunar farside, which contains the most ancient lunar terrains. In particular, we investigated Pre-Nectarian and Nectarian terrains within the so-called Feldspathic Highlands Terrane (FHT) and within the largest impact basin in the whole solar system, namely the South-Pole Aitken basin (SPA). The selection of these terrains has been established according to geologic mapping methods [9].

In this paper, we present the observed crater size-frequency distributions for these regions and present preliminary interpretation of the data, which may provide information on the early evolution of the solar system.

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