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# Modelling the influence of meteoroid collisions on the inventory of cosmic-ray produced nuclides in meteorites

Meier, Matthias M. M. (1, 2)

(1) Naturmuseum St. Gallen, Rorschacherstrasse 263, 9016 St. Gallen, Switzerland (2) ETH Zurich, Institute of Geochemistry and Petrology, Clausiusstrasse 25, 8092 Zurich, Switzerland

## Abstract

Meteorites are windows into the orbital and collisional dynamic of small bodies: they contain a rich inventory of "cosmogenic" nuclides, which have been produced by the exposure of their antecedent meteoroid to cosmic rays. As the production rates of these nuclides are size- and position-dependent, their relative and absolute concentrations can be used to study the meteoroids' collisional evolution through multiple size-stages. Here, I present two models (PyMADOC and PyCRE) developed to study the installation of cosmogenic inventories through orbital and collisional evolution of the meteoroid. I also draw some initial comparisons of the results with observations in some suited sets of meteorites.

## 1. Introduction

Meteorites contain an inventory of both stable and radioactive nuclides (e.g., $^{21}$Ne and $^{26}$Al, respectively) which reflect the meteoroids' history of exposure to high energy particle radiation (cosmic rays) while in space and, at least in some cases, also on the parent asteroid. The absolute and relative concentrations of these cosmic-ray-produced (cosmogenic) nuclides (the "cosmogenic inventory") depend on the size of the meteoroid, the depth below the meteoroid surface at which they were produced, the composition of the meteoroid, as well as the total time of exposure (the cosmic-ray exposure (CRE) age) [1]. Because of this dependence on size and position within the meteoroid, cosmogenic nuclides can in theory also be used to study the collisional history of a meteorite: stable nuclides reflect the integrated exposure conditions, while radioactive nuclides reflect the exposure conditions within their own saturation time (the time until the ratio of the production and decay rates approach unity). Because the typical time of survival against disruption by a collision is roughly on the same order of magnitude as the CRE age (a few 10 Ma for a meter-sized object [2]), a significant fraction of the meteorites we find and analyze today must have experienced at least one meteoroid-meteoroid collision at some point of their CRE history. Here I present two models developed to track the cosmogenic inventory through collisional and orbital evolution. Comparing the output of the model with observations will eventually provide new insights into meteoroid collisions.

## 1. Modelling collisional evolution

Meteoroid collisions frequency is modelled in the PyMADOC part of the model (**Py**thon model of **M**eteoroid, **A**steroid and **D**ust **O**rbital and **C**ollisional evolution). The model starts with an initial population of objects with a user-defined distribution of orbital parameters. The number and characteristic velocity of potential collisional disruptors is determined for each object within the population at its present position (usually in the asteroid belt), based on estimates of these properties [3]. A probability of collisional disruption is determined, and the object is "exposed" to that probability at each time-step. Once a disruptive collision occurs, the object is fragmented into a number of fragments. Each of the new fragments is assigned a new orbit based on the energy of the collision and the fragments mass. Objects with radii below 10 cm are removed from the simulation, as they are unlikely to survive atmospheric entry and are thus not represented among the meteorites in our collections.

## 2. Modelling orbital evolution

Orbital evolution of the objects, i.e. the change of their orbital parameters (here: a, e, i) over time, is also modelled in the PyMADOC part of the model. Orbital evolution affects the cosmogenic inventory in at least two ways: first, if a meteoroid orbit evolves to the point where it reaches an orbital resonance (either one of the many mean-motion resonances with Jupiter, or the ν6 secular resonance with Saturn), its orbit will change, sometimes leading to a complete ejection from the asteroid belt. Because the density of meteoroids is much lower outside the asteroid belt, this will affect the likelihood of further meteoroid-meteoroid. Second, orbital evolution is the dominant process which moves objects into Earth-crossing orbits, such that they might become meteorites which we can study. Orbital evolution of meteoroids is driven by both gravitational and non-gravitational forces. The former include the effects of resonances (implemented in PyMADOC) and encounters with massive asteroids in the belt (not implemented). Non-gravitational forces include Poynting-Robertson drag, the Yarkovsky and YORP effects. Only the Yarkovsky effect is currently implemented in the model [4].

# 3. Modelling nuclide production

In the PyCRE (**Py**thon model for **C**osmic **R**ay **E**xposure) part of the model, the collisional history handed down from PyMADOC (a set of fragment sizes with their associated duration, so-called "size-stages") is processed into a cosmogenic nuclide inventory. I use the production rate model by [1]. Since they only give production rates for certain meteoroid sizes, rates for arbitrary sizes and positions are interpolated. The last-stage meteoroid (i.e., the size at which it enters the Earth's atmosphere) is divided into multiple shells of identical thickness, which are then assigned an appropriate cosmogenic inventory which was installed during the duration of the last size-stage. If the meteoroid had a complex exposure history (i.e., more than one size-stage), the earlier stages have to be included by a more complex process to properly account for the fact that the last-stage meteoroid will likely have been at a non-central position of the preceding meteoroid, leading to unequal irradiation of the different parts of the last-stage meteoroid (e.g., the part of the last-stage meteoroid which was closest to the surface of the preceding meteoroid will be exposed to more cosmic rays than the parts which were located more towards the interior of the preceding meteoroid).

# 4. Comparison with observations

I have identified two sets of meteorite samples which are able to provide "ground truth" data against which the modelling results can be. 1) The growing set of currently ca. 30 meteorites where the orbit of the antecedent meteoroid is known from photographic observation of the entry fireball [5]. The brightness of the fireball provides a direct measure of the mass of the last-stage meteoroid, and multiple known fragments for each fall might be analyzed to get a more complete picture of the variability of the cosmogenic inventory inside that meteoroid. 2) The set of currently ca. 100 "fossil" meteorites found in Ordovician limestone sediments in southern Sweden [6]. These meteorites were likely ejected by a single large collision in the asteroid belt. Since they all derive from the same source, their distribution of their cosmogenic nuclides should be providing insights into the collisional histories of multiple meteoroids, and the collisional evolution of a "fragment cloud" ejected by a large asteroid disruption. Some preliminary insights from these comparisons will be presented at the conference.

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