ACSE-9 Independent Research Project

Inference of Impactor Properties by Inversion of Meteoroid Impact Clusters on Mars with a Fragment-Cloud Model

Project Plan

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1 Overview

Analysis of impact craters on bodies within the solar system can give insight into properties of meteoroids forming these craters. While there are empirical relationships for estimating the size of a crater from impactor properties and vice versa (e.g. Holsapple, 1987), these relationships are not directly applicable to small impacts on planets with an atmosphere. When impacting these planets, small-sized meteoroids experience significant deceleration, mass loss due to ablation, and potential break up before impacting the ground. As a result of these processes, they typically produce clusters of impact craters, or only leave a strewn field of small meteorites if most of their kinetic energy has been deposited in the atmosphere.

The aim of this project is to invert impactor properties from data in a recent survey of Martian impact crater clusters (Daubar et al., 2019). We will investigate whether stochastic inversion methods, such as Markov Chain Monte Carlo (MCMC), are a viable approach for this problem. MCMC models, such as the Gibbs sampler combined with the Metropolis-Hastings algorithm (Gelfand and Smith, 1990), have been a very popular black box inversion method in many research areas (e.g., in epidemiology Flaxman et al., 2020). In order to use an MCMC method, a high-performance numerical model of atmospheric descent and crater cluster formation is needed.

A popular way of modeling these processes is to build on the standard meteor physics equations of motion and ablation (e.g. Opik, 1958), which are a set of ordinary differential equations (ODEs) treating the meteoroid as a homogeneous, spherical or ellipsoidal body. Break up is modeled to occur when the pressure difference between the leading edge and the trailing edge of the meteoroid exceeds the aerodynamic strength of the meteoroid material. The exact mechanism of break up is subject to ongoing research. Most break up models use either a "pancake" approach, or a discrete fragmentation approach (Register et al., 2017).

More recently, a combination of the two approaches, called the fragment-cloud model (FCM), was proposed by Wheeler et al. (2017). The concept behind this model was first presented by Mehta et al. (2015). It combines the separate-wake fragments model (Passey and Melosh, 1980; Artem'eva and Shuvalov, 1996) with a pancake-like model: When the meteoroid's strength is exceeded, it splits into a debris cloud plus several discrete fragments, which are all treated independently from each other after separation. In a subsequent publication, Wheeler et al. (2018) extended their model (cf. fig 1) and were able to demonstrate excellent agreement between simulated energy deposition and that inferred from light curves of four recent meteoroid impacts on Earth.

Newland (2019) applied the FCM model and key conclusions from the Wheeler et al. (2018) paper to the formation of impact crater clusters on Mars. They were able to demonstrate that the FCM model, with the right parameters, was able to reproduce crater clusters with a similar distribution of certain characteristics compared to observations collected by Daubar et al. (2019). They also showed that simpler models, like the discrete fragmentation approach or the FCM model without varied initial structures, as first proposed by Wheeler et al. (2017), were unable to reproduce the observed distributions of cluster characteristics.

Based on these promising results, we will use the FCM model for our inversion problem. However, a key downside of MCMC inversion methods is their heavy computational costs. They typically run the underlying model thousands of times to generate an accurate input space distribution. In our case, the underlying FCM model is computationally demanding in its own right. Equations for potentially hundreds of fragments and debris clouds have to be solved numerically for each impact.

The FCM implementation by Newland (2019) was based in pure Python. A single simulation run took on the order of seconds to

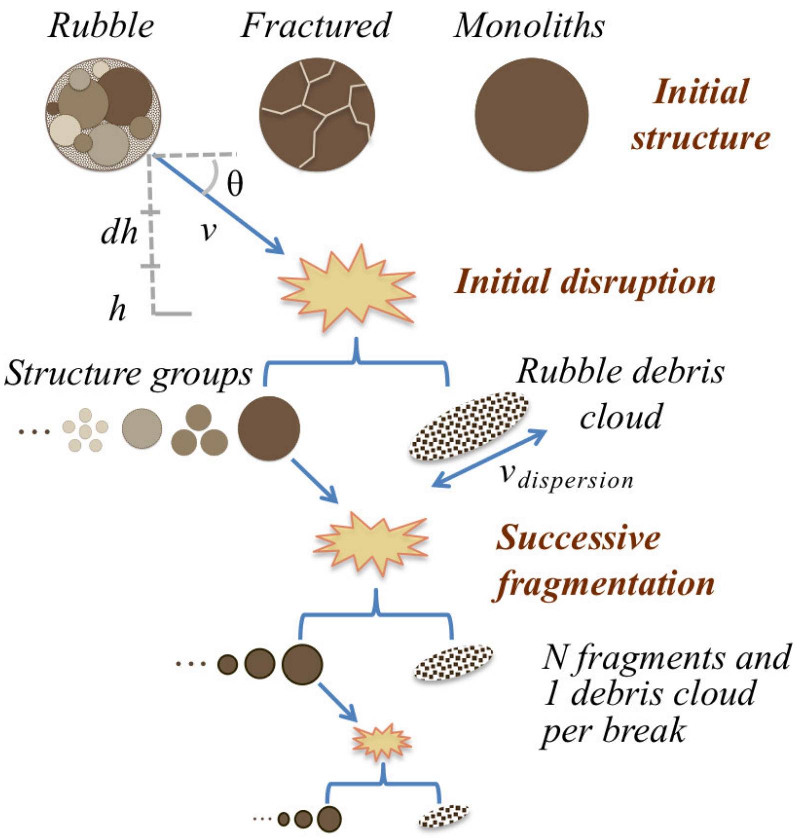

Figure 1: FCM model diagram, taken from Wheeler et al. (2018). A meteoroid is modeled to enter a planetary atmosphere with a speed v and a trajectory angle θ relative to the ground. When the ram pressure exceeds its aeordynamic strength at height h above the ground, it fragments into different structural groups, and a debris cloud. The debris cloud is described with a "pancake"-style model. The fragments descend further into the atmosphere and may undergo successive fragmentation when their aerodynamic strength is exceeded.

tens of seconds, and was limited, by nature of its pure Python implementation, to be single-threaded. To facilitate fast iteration and realistic, scalable run times for the inversion problem, we aim to develop an open source FCM implementation in a fast, compiled language, C++, along with a Python API. We expect the performance to increase by at least two orders of magnitude from this switch on its own. If time permits, we will investigate further optimisations.

2 Project Plan

This project is divided into two parts. First, the goal is to develop a high quality FCM implementation in C++ based on the work by Newland (2019) (sec. 2.1). Second, the aim is to estimate impactor properties from crater cluster data, using the FCM implementation from the first part combined with an MCMC inversion method (sec. 2.2). An overview of all tasks and milestones is in table 1.

2.1 C++ FCM Implementation

The goal is to implement C++ numerical algorithms, which integrate all differential equations of the meteoroid and its fragments after breakup, along with a Python API. In order to be able to predict impact crater locations in debris fields, all objects have to be simulated in three dimensional space. We will closely follow the work by Newland (2019), who has already implemented three dimensional trajectory calculations.

It is important to note that the FCM model does not represent a detailed simulation of the actual processes of ablation, airflow and break up. Rather, it models these complex processes in a simplified form, based on results of more detailed studies involving 3D hydrodynamic simulations of asymmetric meteoroids descending through the atmosphere (e.g. Artem'eva and Shuvalov, 1996; Artemieva and Shuvalov, 2001). The aim is to have the results be a close enough approximation, while cutting down on computational complexity by reducing the entire process to a set of ODEs.

As noted in Newland (2019), the FCM can be simplified to replicate both a pure cloud model and a pure fragmentation model. The aim is to make the implementation modular such that it is possible to accommodate most flavours of both classes of simpler models Artem'eva and Shuvalov (1996); Artemieva and Shuvalov (2001); Register et al. (2017); McMullan and Collins (2019). Since all these models build on the standard meteoroid equations (e.g. Opik, 1958), the actual differences in implementation are somewhat minor. However, one thing that we have to look out for is that a poor implementation of these switches between different methods could dramatically decrease the cache hit rate, which typically has a significant impact on performance.

2.2 Crater Cluster Data Inversion

With the efficient code of part one, the goal is to investigate the inverse problem of estimating impactor properties from crater cluster data. Crater cluster data from Daubar et al. (2019) has already been used by Newland (2019), and is readily available. We will first conduct a literature review about potential inversion methods.

If we decide to use an MCMC method, a cost function is needed, which the algorithm will try to minimise. Since there is a lot of randomness involved in meteoroid break up, having the algorithm try to replicate the exact same crater cluster formation as in the input image is most probably ill-advised. A more promising approach seems to be to extract features from the crater cluster image, such as Newland (2019) has done in his work, and try to estimate impactor properties that most likely result in a cluster with similar features.

An important consideration is which impactor properties to invert for, and which ones to keep fixed. Necessarily variable are the meteoroid mass, radius, and its velocity and angle relative to the planet's surface at the start of atmospheric entry. These are all continuous parameters. However, in their study, Wheeler et al. (2018) also varied the internal composition of impactors, while Newland (2019) kept it fixed for their Monte Carlo analysis. Most of the parameters for internal composition of impactors, as laid out in Wheeler et al. (2018), are discrete values, which might require a special flavour of MCMC algorithm.

Overall, this part of the project is highly exploratory in nature. At first, the focus will be on finding a small set of variable parameters for which we can find an inversion method, together with a suitable cost function, that actually converges. If time permits, we will investigate expanding the set of variable parameters.

3 Success Criteria

Producing a high performance FCM implementation (sec. 2.1) is the primary objective of this project. The implementation should be:

(i) high performance; two orders of magnitude improvement compared to both Mehta et al. (2015); Newland (2019).

(ii) modular; allow the user to choose between different fragmentation approaches, numerical integration schemes, degrees of randomness etc.

(iii) extensible; keep potential extensions in mind when deciding on code structure, make good documentation and tests.

(iv) user friendly; easy install process, usage examples, detailed documentation, sensible parameter presets.

Should it be the case that achieving these objectives requires considerably more time than anticipated, we might shift the focus of this project entirely onto the goals outlined in sec. 2.1. We could investigate further improving performance by making the code multi-threaded.

If the milestones in sec. 2.1 can be hit without significant delays, we will proceed with the second part (sec. 2.2). The objectives are as follows:

(i) Gain a detailed overview of available MCMC (or similar) methods.

(ii) Implement a suitable cost function.

(iii) Use MCMC for inversion of meteoroid mass, density, velocity, angle, and strength, while keeping internal structure fixed.

(iv) Investigate including the internal structure into the inversion process.

These items are ordered to be progressively more ambitious, and do not have to all be achieved. The priority is to gain and document a detailed understanding of results at each step, rather than necessarily having some less detailed results for all objectives.

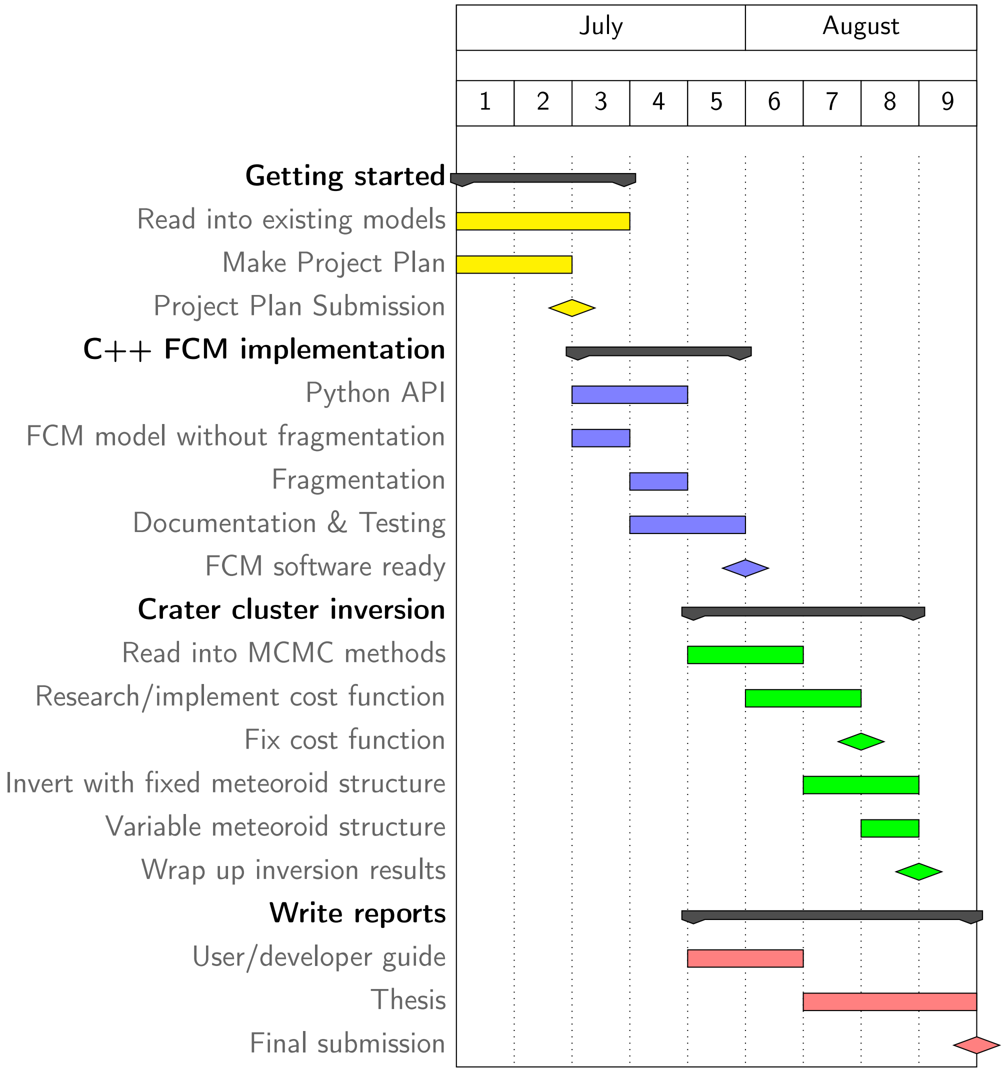

Table 1: Project milestones

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