DIFFUSION-LIMITED AGGREGATION MODEL FOR ARANEIFORM PATTERN FORMATION

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Introduction: After 5 martian years (MY) of repeated coverage of seasonal polar processes, the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) for the first time has imaged new araneiforms forming under current climatic conditions [1]. Araneiforms (or more colloquially, spiders) are radially converging systems of branching troughs often exhibiting fractal properties. Kieffer et al. [2] proposed a model for formation of araneiforms and seasonal fan-shaped deposits and blotches associated with them. The model is based on solid-state greenhouse effect acting in spring underneath a seasonal CO_2 ice layer and is generally accepted by the community. It reasons that the araneiforms as topographical features are created by a stochastic-probabilistic process of erosion by the compressed flow of CO_2 gas underneath an impermeable ice layer. The HiRISE observations of the new araneiform supported this assumption: some of araneiform troughs extended from one year to the other, new tributaries developed on the previously existing troughs, but also a part of the trough from MY 31 was observed to disappear in MY 32. This assumption of araneiform development from simpler to more complex systems is also supported by the variety of the araneiform morphologies: some of them have well developed branching of long troughs, some show only one or two troughs merging together, and others even show only one short arm connected to a pronounced center [3]. Our premise is that there is a correspondence of these observational differences to different stages in araneiforms' development: simpler looking and mostly smaller araneiforms are in the early stage of their development while the more complex ones are older.

There are several parameters that can influence the apparent age of an araneiform. The most influential parameter is substrate properties (such as material strength, compaction and cementation degree, water ice content, etc.) that directly determines erodability.

Another important parameter is the erosive force of the sub-ice gas flow, which relates to the overall energy content of the jet eruption. This energy in turn is controlled by the ice layer properties: firstly, by the amount of transmitted light, and secondly, because higher ice strength can store CO_2 gas at a higher pressure.

There is one parameter to influence the real age in contrast to the apparent age of araneiforms: if the retreat of the permanent polar cap was not symmetric then some areas were still covered at times when other areas already experienced the erosive forces of seasonal cap sublimation. Because of this, differences in apparent age might have been caused by different exposure to the erosive forces.

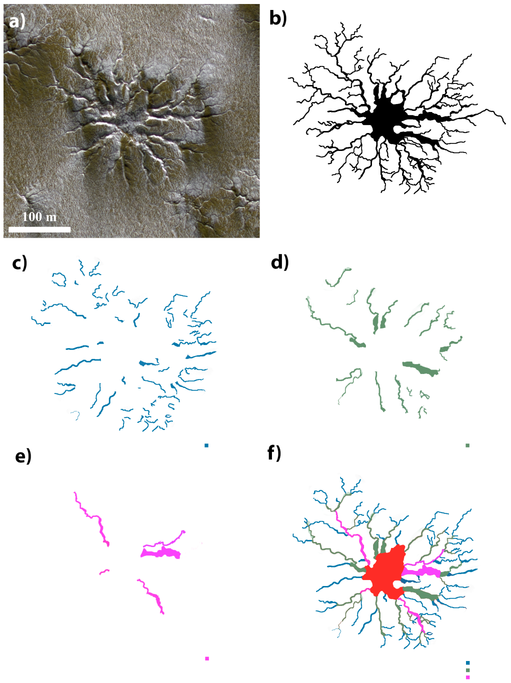

Figure 1: An example of morphological analysis of one araneiform pattern. The number of different degree tributaries, surface density of tributaries of different degrees, and their ratios are used as morphological parameters of the drainage network.

Several authors [2-5] noticed the similarity of araneiform patterns to dendrites, specifically to fractal river patterns. Both processes involve erosion of the substrate by a flow of a moving agent: water in the case of rivers, and pressurized gas in the case of araneiforms. Yet, river erosion is fundamentally different in that it is governed by gravity. The process of creation of the araneiform terrains is specific to Mars and has no direct terrestrial analog. Araneiforms are created by gaseous flow erosion – it does not follow the topographical gradient, but rather the gradient of gas pressure inside the chamber underneath the ice layer.

Araneiforms morphology: We will use specific descriptors for araneiform patterns to constrain the diffusion limited aggregation (DLA) model (described below) by comparing the observed patterns with model-simulated araneiform shapes. We need to ensure that values for the fractal dimension, branching ratio, and

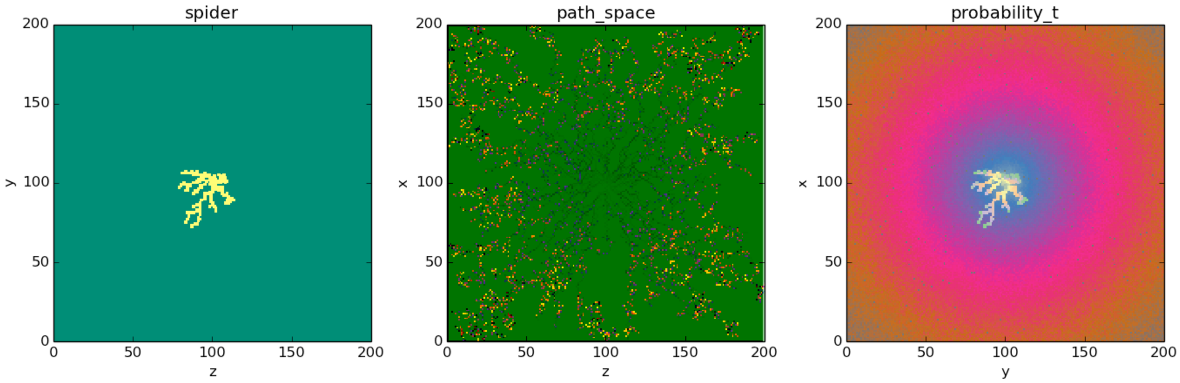

Figure 2: An example of 2D DLA model run. Left panel shows resulting dendrite cluster; middle panel is a set of paths by all random walkers used in the run; and the right panel is a probability field that governs the movement of the random walker.

branching angles for araneiforms are reproduced by the modeling. For this we determined these values for several selected araneiform locations using HiRISE images.

Fig. 1 shows an example of morphological analysis of a randomly selected araneiform pattern following the Horton-Strahler stream ordering scheme [8, 9]. The araneiform pattern is divided into a set of tributaries of different degrees. The first degree tributary is the one that has no tributaries, two first degree tributaries merging into one form a second degree tributary, and so on. Panels c-e show first to third degree tributaries for the example araneiform accordingly. The surface density of tributaries of different degrees, their absolute number and ratios are descriptive parameters of the drainage network that can be used for the comparison with the models.

DLA model: We have implemented a 2-D DLA model to describe the araneiform structures with the aim to investigate the relationship between the physical processes that are modifying araneiforms. The diffusion limited aggregation model is a strictly mathematical model for pattern formation and was first introduced as a model for irreversible colloidal aggregation [7]. It was later realized to be applicable to other naturally appearing patterns (like electrical discharge paths, mineral inclusions in rocks, spread of bacteria colonies, etc.) with the main common physical feature being that the transport of material is dominated by diffusion and not convection. Most importantly, the parameters of the DLA model that influence the appearance of the resulting structure were shown to be related to the physical processes (erosion in our case) that create the structures observed.

A short description of the DLA model is as follows: consider a domain made of a 2-dimensional grid of points, one particle to serve as a non-moving seed for a future cluster and another particle to perform a random walk controlled by probabilities given to each grid point. To allow for sufficient 'randomness' the random walker should start in a significant distance from the clustering seed. At the end of its walk the particle might either have left the model domain or irreversibly adhered to the clustering seed. If it adheres to the cluster, this growth of cluster represents the growth of the araneiform pattern and each adherence represents an incremental erosion event. Repeating these random walks many times will make the cluster grow in size. The clusters that are generated by such a model are both highly branched and fractal. An example is shown in Fig. 2. The implemented DLA algorithm works in 2 dimensions, i.e. it can create an "image" of the dendrite. From the nature of DLA model formulation the number of parameters that govern the morphological structure of a dendrite may be reduced to the probability of surface erosion at a given drag force applied to the surface. We can modify the governing probability field in both spatial and temporal domains, which leads to the variety of morphologies of the resulting dendritic clusters.

We will present morphological analysis for multiple locations inside martian polar regions with active araneiform terrains, including unconventional shapes like lace terrain. We will discuss how the DLA model parameters are related to the physical properties of the existing araneiform terrains.

References: [1] Portyankina et al., 2017, Icarus 282, pp. 93-103 [2] Kieffer et al. 2006, Nature 442 [3] Hansen et al. 2010, Icarus 205, pp. 283-295 [4] Piqueux et al., 2003, JGR 108, E8, 5084 [5] Pommerol et al., 2011, JGR 116, E08007 [6] T A Witten and L M Sander., 1983, Physical Review B, 27(9) [7] Horton, 1945, GSA Bulletin, 56(3):275 [8] Strahler, 1957, AGU Transactions 38(6)