CRATER SATURATION OF SOLAR SYSTEM SURFACES: INSIGHTS FROM SPATIAL STATISTICS.

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Introduction: For several decades there has been a debate over whether densely cratered surfaces in our solar system are in "saturation equilibrium" [e.g., 1-7; a state where crater density reaches an (quasi-) equilibrium]. Saturation equilibrium is critical to understand because otherwise the crater distribution shape and/or flux can be misinterpreted. This work uses spatial statistics (quantitative measures of objects' distributions in space) to constrain whether cratered surfaces throughout the solar system are in saturation.

Background: Traditional approaches to studying crater saturation have focused on crater density and crater size-frequency distribution (SFD) slope [e.g., 1-5]. The use of spatial statistics was introduced by Lissauer et al. [6] and Squyres et al. [7]. They proposed that a crater distribution would become more spatially uniform (more evenly spaced) as it reached saturation. Their reasoning was that as a crater distribution approached equilibrium the gaps occurring in a random distribution would become occupied, thus producing a more even distribution. Squyres et al. [7] combined a numerical simulation of a steeply-sloped SFD (cumulative slope=-2.7) with observations of heavily cratered terrains on Rhea and Callisto to empirically show this hypothesis could be valid *for this case*. However, neither group expanded the study to other slopes or fully explored why the gaps should get filled in as crater density increased.

Methods: My work combines new numerical simulations with new observations of cratered terrains – continuing the approach of Squyres et al. [7]. For the spatial statistic component of these analyses, I use the Z-statistic for points, initially developed by Clark and Evans [8]. The Z-statistic measures the deviation of a spatial distribution away from a random (Poisson) distribution using a straightforward comparison between the average observed nearest neighbor value and the expected nearest neighbor value for the random distribution. A value of Z=0 represents a perfectly random distribution, while a value of Z>0 would be a more uniform distribution (Z<0 is more clustered). However, because craters are areal features, I also use a variation of the Z-statistic (Z_a) developed in Squyres et al. [7] that accounts for the craters' areas in the calculation of the expected nearest neighbor.

My simulation includes parameters for the input crater SFD slope, importance of very small craters in erasing craters ("sandblasting"), effectiveness of ejecta in erasing craters, and the threshold percentage of remaining rim below which a crater is consider erased. The only process erasing craters is the formation of new ones. At the end of a simulation the crater equilibrium density and Z/Z_a values are recorded at saturation.

For the observations I measure crater diameters and locations for selected terrains throughout the solar system. Terrains are selected for a range of crater densities to explore if and at what point saturation occurs and how that might vary for surfaces exposed to different impactor populations. After the crater distributions are compiled, I compute the cumulative crater density and both Z values for comparison with the simulations.

Results: First, I have verified that crater distributions would become more spatially uniform as they reach saturation [9]. This initial work using uniformly sized craters demonstrated that it is the areal nature of craters (a new crater must form in a gap in order to not erase a preexisting one) that cause the distributions to become more uniform as they approach saturation equilibrium. However, real crater SFDs are not composed of uniformly sized craters and how the craters erase one another becomes complex.

Therefore, I have run simulations broadly varying crater SFD slope and the other parameters (Table 1) to determine how they affect conditions for saturation and the Z-statistic. The results of these simulations are summarized in Fig. 1, which plots the saturation equilibrium crater density vs. Z or Z_a. In these plots colors represent slopes and shapes represent other simulation variables as indicated. Overall, the simulation results indicate that crater SFD slope is the most important factor in determining at what density saturation occurs and how uniform the distribution would become. Crater distributions with a shallow slope (= -1; orange) will reach saturation at lower densities than populations with steeper slopes (smaller negative values). Furthermore, crater distributions with a steep slope (= -3; purple) will become more uniform in saturation than populations with shallower slopes. Variation of the other parameters cause only minor fluctuations in the density and Z values in comparison to the major differences between slopes. Lastly, the general patterns are similar whether considering Z or Z_a.

Table 1. Simulation Parameters.

Parameter	Values
Input Crater SFD slope	-1, -2, -3
"Sandblasting": Larger value = bigger influence	3, 6, 9, 12, 15
Ejecta Size (x crater radius)	1.1, 1.3. 1.5, 1.7, 1.9
Rim Percent Remaining	30, 40, 50

The next step is to compare the density and Z values for observed regions (red bars) to the simulation results. Fig. 2 shows these comparisons subdivided by

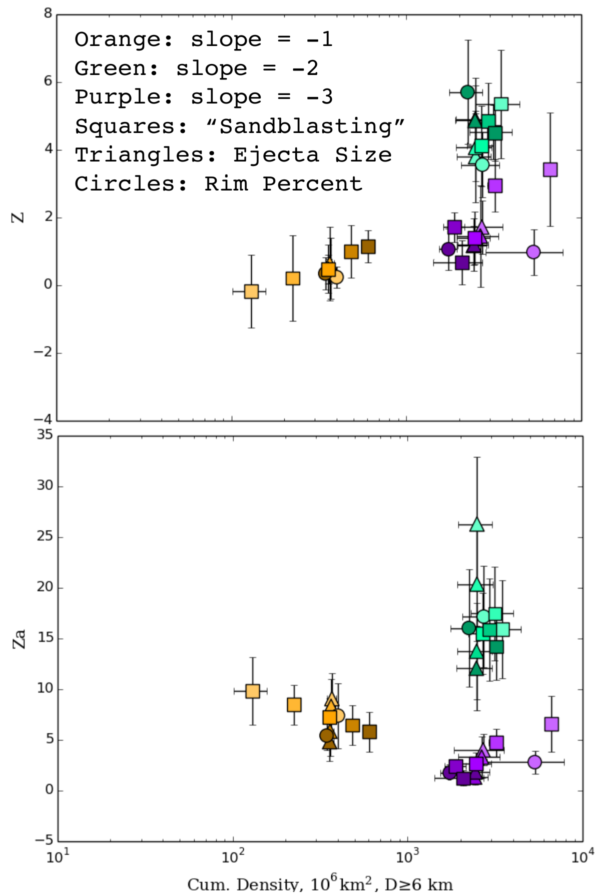

Figure 1. *Simulation results.*

crater size for the Z_a value only (results are not significantly different for the Z value). Before these data can be used to infer if terrains are in saturation, two important pieces of information should be noted. 1) The crater SFD cumulative slopes of the terrains presented here are around -2, except Dione 3 (D3), Miranda 1 (M1), and Ariel 2 (A2), which are around -1. 2) Crater distributions with cumulative slopes ≤ -2 before saturation have slopes of about -2 after they reach saturation, while slopes > -2 more or less retain their initial slopes in saturation [e.g., 3]. Therefore, the densely cratered terrains with slopes around -2 that correspond to the simulation results for input slopes of -2 and -3 are likely in saturation equilibrium (Ms, E, D1, D2, R, Ib, Id-small, U, O). Conversely, the less densely cratered terrains with slopes around -2 that fall outside of these simulation results are not likely saturated (Gb, Gd, Id-large, M2, A1, T). Meanwhile, none of the terrains that have slopes around ~1 match with values derived from the simulations, indicating they are not likely saturated. Overall, these results suggest there are common cumulative densities at which saturation occurs for the outer solar system, which is diameter dependent: ~80 per 10^6 km^2 for D ≥ 25 km craters and ~2000 per 10^6 km^2 for D ≥ 6 km craters.

Future Work: The work discussed here using basic cumulative slope values that do not change with diameter demonstrates the value of spatial statics in studying crater saturation. However, real crater distributions typically have SFDs that change slope with diameter. Thus, I am currently running simulations that use crater SFDs with varying slopes. Results of these simulations will be compared with results of the single slope simulations, along with the observations presented here and new observations of inner solar system surfaces. Implications will be discussed.

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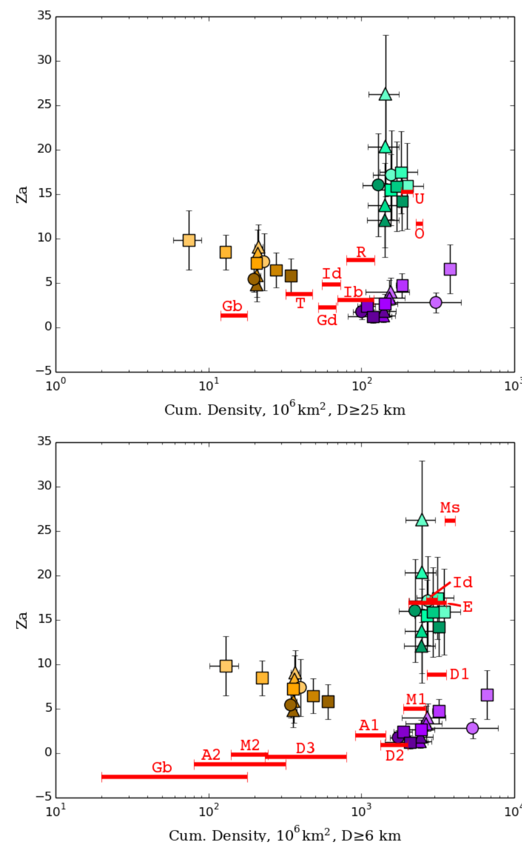

Figure 2. *Comparing observations of cratered terrains (red bars) to simulation results. Top: D~25-200 km craters; Bottom: D~6-50 km craters. Colors and shapes as in Fig. 1. Terrains: Ganymede dark (Gd), Ganymede bright (Gb), Mimas (Ms), Enceladus (E), Dione 1 (D1), Dione 2 (D2), Dione 3 (D3), Rhea (R), Iapetus dark (Id), Iapetus bright (Ib), Miranda 1 (M1), Miranda 2 (M2), Ariel 1 (A1), Ariel 2 (A2), Umbriel (U), Titania (T), and Oberon (O).*