
Introduction

That the population of craters on Venus cannot be distinguished statistically from a spatially random distribution was recognized early on [1] and is a powerful constraint on models of Venus's resurfacing history. Schaber et al. [2] and Strom et al. [3] have interpreted the cratering record to indicate that Venus experienced a global resurfacing event about 300 m.y. ago, followed by a dramatic reduction of volcanism and tectonism, with only 4-6% of the planet resurfaced since then. In support of this thesis, Strom et al. reported that a chi-square test of the distribution of craters with elevation shows that the craters are randomly distributed vertically as well as horizontally. Recent formal comments on [3] by Herrick et al. [JGR-submitted] include the statement that "incorrect observations were input into inappropriate models whose output was misinterpreted." They attack, among other things, the use of a chi-square test to compare the elevations of craters with the overall hypsometric distribution of Venus; the observed crater elevations should instead be compared with the planetary elevations as sampled by a fictitious set of randomly distributed craters. Because of this and other "problems" with [3], Herrick et al. claim that the planet-wide resurfacing model is untenable. Strom et al. will respond to the full set of criticisms of their paper once the comment by Herrick et al. is accepted for publication. In this abstract, we report on a re-examination of the question of the statistical uniformity of the crater population with elevation. We have remeasured the sizes and locations of a substantial fraction of the craters, and redetermined their elevations from the final Magellan altimetry dataset (the earlier result was based in part on pre-Magellan data). We have also extracted physical-properties data for the craters and their surroundings. Finally, we have carried out more powerful statistical tests of the uniformity of the crater distribution based on the new data, with statistical significances evaluated by Monte Carlo simulation. Our results confirm those of [3]: craters are uniformly distributed in elevation.

Revised Crater Database

We have recently revised and updated the crater database originally reported in [2]. Crater positions and diameters in this database were originally determined from photographic prints of Magellan images. We therefore compared these values with those measured by Herrick and Phillips [4] from digital data. After digitally remeasuring the positions and sizes of the majority of craters for which significant discrepancies (>0.1") existed (as well as all craters larger than 30 km in diameter), we concluded that the measurements from hardcopy are indeed less accurate, and provisionally adopted Herrick and Phillips's positions and diameters for the remaining cases of discrepancy. We are currently remeasuring the positions and diameters of all craters, as well as the areas of floor and external deposits associated with them (including outflows) [5]. It should be emphasized that the changes to the database are relatively small, typically no more than a few tens of kilometers.

Elevation and Physical Properties Measurements

We used the database of crater positions and diameters to automatically measure elevations from the Magellan global topography data record (GTDR, [6]). We defined three zones of equal area—the crater interior (0 to 1 crater radius), the exterior or ejecta (1 to 2 radii), and the far exterior beyond the ejecta (3 to 2 radii)—averaged the values of all GTDR pixels in each zone, and converted the data number to an elevation value. For smaller craters, one or more zones may not contain any pixel centers; in such cases, we used the value of the GTDR pixel closest to the center of the crater. We measured values of emissivity, reflectivity, and RMS slope in a similar fashion from the GEDR, GREDR, and GSDR datasets, respectively, and measured backscatter crosssection from a global mosaic of Magellan images reduced to the 4.6 km/pixel resolution of the GxDRs.

Statistical Analysis

For each crater zone and each measured quantity we evaluated several statistical measures of uniformity based on the empirical distribution function, or EDF [7]. The EDF for, say, elevation can be thought of as a plot of fraction of craters below a given elevation versus fraction of the planetary area below this elevation. Tests based on the EDF are considerably more powerful than chi-squared tests because they do not require binning the data, a process which destroys information. Tables of significance for the common EDF tests are available, but we evaluated the significance of our results by Monte Carlo simulation. For each zone and dataset, we sampled the GxDR with a set of craters with the same diameters as the real craters but random locations, evaluated the EDF statistics, and repeated this process a total of 100 times. We also evaluated EDF statistics for the latitudes and longitudes of craters; because there is no sampling effect, the tabulated significances could be used for these. Table 1 shows the significance levels for the Cramér-von Mises $W^2$ statistic (for longitude, the related Watson $U^2$ statistic for data on a circle was used) [7]. This is the fraction of the 100 Monte Carlo simulations that resulted in the observed $U^2/W^2$ value or a more extreme value; small values therefore signify a non-random distribution.
The bins in diameter were chosen so that an equal number of craters falls in each bin. The results are
We postulate that this is an observational selection effect, caused by the difficulty of identifying very small
density in different elevation bins indicate that the small craters are relatively deficient at high elevations.
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All craters
The values in the surround, which are distributed differently from the whole planet for all parameters, are of
We also investigated the elevation distribution for subsets of the crater population with different sizes.
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on random distribution, whereas larger craters clearly have random elevations. Plots of the crater
density in different elevation bins indicate that the small craters are relatively deficient at high elevations.
We postulate that this is an observational selection effect, caused by the difficulty of identifying very small
craters on the rugged highland terrain.

Table 1 -- Significance levels of observed value of $U^2$ statistic for crater properties

<table>
<thead>
<tr>
<th></th>
<th>Elevation</th>
<th>Emissivity</th>
<th>Reflectivity</th>
<th>Slope</th>
<th>Backscatter</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior</td>
<td>&lt;0.01</td>
<td>0.20</td>
<td>0.14</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.20</td>
<td>&gt;0.25</td>
</tr>
<tr>
<td>Ejecta</td>
<td>0.08</td>
<td>0.10</td>
<td>0.15</td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Surround</td>
<td>0.54</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

Results and Interpretation

We note in passing that the large significance values for latitude and longitude confirm that the spatial distribution of craters is random, though the test used here is less sensitive than that of [1]. The result of Strom et al. [3] that crater elevations are random is also confirmed, provided the elevations are measured outside the craters. Elevations within craters are different from the planet as a whole (biased downward), as is to be expected given that craters are topographic features; the effect would be even stronger but the GTDR dataset only resolves the interior of about the largest 1/4 of all craters.

We also investigated the elevation distribution for subsets of the crater population with different sizes. The bins in diameter were chosen so that an equal number of craters falls in each bin. The results are shown in Table 2: the smallest 1/4 of the craters are distributed nonrandomly and the smallest 1/2 borders on nonrandom distribution, whereas larger craters clearly have random elevations. Plots of the crater density in different elevation bins indicate that the small craters are relatively deficient at high elevations. We postulate that this is an observational selection effect, caused by the difficulty of identifying very small craters on the rugged highland terrain.

Table 2 -- Significance levels of $U^2$ statistic for crater elevations as a function of size

<table>
<thead>
<tr>
<th></th>
<th>&lt;14.2 km</th>
<th>&gt;14.2 km</th>
<th>&lt;7.85 km</th>
<th>7.85-14.2 km</th>
<th>14.2-25.7 km</th>
<th>&gt;25.7 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>All craters</td>
<td>0.08</td>
<td>0.08</td>
<td>0.57</td>
<td>&lt;0.01</td>
<td>0.46</td>
<td>0.43</td>
</tr>
</tbody>
</table>

There is no reason to expect that the physical properties of the crater interiors or ejecta will obey the same statistical distribution as the planet as a whole (although in the cases of emissivity and reflectivity they do). The values in the surround, which are distributed differently from the whole planet for all parameters, are of more interest. The apparent biases are 1) away from extreme emissivities and extreme RMS slopes, and 2) toward high reflectivities and high backscatter crossection. All of these departures from the global distribution, though significant, are far less pronounced than the corresponding departures for splotches [8]. We are currently seeking to understand whether these results are 1) an artifact caused by the unresolved small craters (for which the surround measurements may be contaminated by crater properties), 2) a result of modification of the surface outside the ejecta (e.g., halo and parabola materials), or 3) a potential clue to the geologic history of Venus.

Discussion

As claimed by Strom et al. [3], the distribution of venusian craters appears random in elevation as well as in horizontal location. This observation is consistent with, and confirms our belief in, a model in which global resurfacing ended abruptly ~300 m.y. ago and was followed by limited geologic activity. We wish to emphasize that neither Schaber et al. [2], Strom et al. [3], nor the present authors have claimed that there has been no geologic activity since the global resurfacing (the bugaboo of "a geologically static planet" attacked by Herrick et al.). The statistical tests must be interpreted with some care: they do not mean that the crater distribution is perfectly uniform and modification effects are hence nil. Rather, they indicate that any departures from uniformity caused by recent geologic activity are too subtle for us to identify, given the small crater population. Furthermore, these results only limit what can be learned from looking at the spatial distribution of craters and nothing else. It is entirely possible that examining the statistics of craters grouped according to some a priori criterion (physical properties as the above results suggest, or geologic environment [9] will lead to significant results and shed some light on the nature and extent of recent geologic activity on Venus.

References Cited