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Probabilistic constraints from existing and future radar imaging on volcanic activity on Venus

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ABSTRACT

We explore the quantitative limits that may be placed on Venus' present-day volcanic activity by radar imaging of surface landforms. The apparent nondetection of new lava flows in the areas observed twice by Magellan suggests that there is a ~60% chance that the eruption rate is ~1 km^3/yr or less, using the eruption history and area/volume flow geometry of terrestrial volcanoes (Etna, Mauna Loa and Merapi) as a guide. However, if the detection probability of an individual flow is low (e.g. ~10%) due to poor resolution or quality and unmodeled viewing geometry effects, the constraint (<10 km^3/yr) is not useful. Imaging at Magellan resolution or better of only ~10% of the surface area of Venus on a new mission (30 years after Magellan) would yield better than 99% chance of detecting a new lava flow, even if the volcanic activity is at the low end of predictions (~0.01 km^3/yr) and is expressed through a single volcano with a stochastic eruption history. Closer re-examination of Magellan data may be worthwhile, both to search for new features, and to establish formal (location-dependent) limits on activity against which data from future missions can be tested. While Magellan-future and future–future comparisons should offer much lower detection thresholds for erupted volumes, a probabilistic approach will be required to properly understand the implications.

1. Introduction

There is a great interest in understanding the divergent evolution of the sister worlds i.e. Earth and Venus, and possible present-day volcanic activity is an important but unknown feature of Venus' present state. Specifically, estimates of Venus' activity range over three orders of magnitude (see later.) Volcanic activity through time is likely a major factor in controlling the atmospheric composition and also the greenhouse effect and Venus' habitability. In the last two decades, these questions have taken on a wider context with the discovery of many exoplanets subjected to stronger insolation than the Earth.

While circumstantial evidence of recent volcanism on Venus exists (the near-IR observation of low-emissivity areas, interpreted as fresh unaltered lavas, (Smrekar et al., 2010)), and also the association of variations in near-IR emission with volcanic regions (Helbert et al., 2008), no 'smoking gun' of present-day activity has been observed so far.

Near-infrared observations have been proposed to detect the incandescent glow of very recent lavas (e.g. Hashimoto and Imamura, 2001; Shalyagin et al., 2012), although the blurring of near-IR signals by the cloudy atmosphere limits the resolution to ~100 km^2. Less recent warm-at-depth lavas could be detected as thermal anomalies in microwave radiometer data (e.g. Bondarenko et al., 2010), but claims of such anomalies rely on uncertain decorrelation of microwave backscatter/emissivity variations and are not considered robust (P. Ford, personal communication, 2014).

Thus more direct (or at least, independent) means of detecting present-day volcanic activity are desirable. The morphological detection in radar imaging of lava flows that were not present in Magellan data would be a simple approach (since lava flows on Venus have a characteristic morphology and are at least sometimes radiometrically distinct – see Section 5 – from the surfaces on which they are superposed) but the chances of success have not (to this author's knowledge) been quantitatively reported. In this paper we examine the likelihood of detection of new volcanic features on Venus by radar mapping and the constraints thereby afforded on the present-day lava eruption rate. Note that throughout this paper we consider eruption rate to be only that expressed as new surface deposits (i.e. lava flows, ash deposits etc.) Intrusive volcanism or other magmatism is not considered.

We adopt a somewhat Bayesian statistical perspective on the problem. Whereas most investigators would like to assert a preferred value for eruption rate, it is impossible to develop a more general measure of confidence (i.e. probability as strength of belief in a Bayesian sense) without introducing judgements on individual

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analyses. We prefer to consider all values possible with non-zero probability, recognizing that 100% certainty requires perfect knowledge, which can never be attained. By embracing the uncertainty of the situation, however, we can apply what information does exist to at least bound the probability distribution.

Stimulated by a recent workshop on Venus hosted in Catania, Sicily, in the shadow of Mt. Etna, we use this volcano as a representative guide for terrestrial volcanoes, and justify this example by showing that Mauna Loa and Merapi have similar statistical properties. We additionally set a quantitative context for volcano volumes and eruptions using compiled terrestrial data.

2. Venus eruption rate

Since Earth and Venus are of similar size and mass, the present-day eruption rate of Earth makes a useful starting point for discussion. Global terrestrial magmatism amounts to about 30 km^3/yr (Head and Wilson, 1986) of which only a fraction, say 3–10 km^3/yr, is expressed as extrusive volcanism on the surface. The latent and sensible heat of subaerial and subsea lavas account for only about ~10% of the total loss of heat through the uppermost part of the Earth's crust (Francis, 1993), which is dominated by conduction (although, of course, the transport of heat from the deeper interior is dominated by convection). Thus, assuming similar radiogenic heat production in the interior and the same energy of accretion for Venus, one might a priori expect a similar rate of volcanism, i.e. a few km^3/yr.

Phillips et al. (1992) suggest that the impact crater distribution on Venus can be explained by an equilibrium resurfacing model with an eruption rate of ~1 km^3/yr, broadly comparable with intraplate volcanism on Earth (0.33–0.5 km^3/yr). On the other hand, Strom et al. (1994), using the small fraction (~2.5%) of lava-embayed impact craters as a guide, instead favor a resurfacing 300 million year ago with an ongoing lava production rate of only 0.01–0.15 km^3.

Finally, dividing the total observed volume of volcanic constructs on Venus by an assumed resurfacing age of 500–800 million year yields a lava eruption rate of 0.01–0.017 km^3/yr (Crumpler et al., 1997). This represents an extreme lower limit for the long-term average, in which it is assumed that no material has been removed by erosion.

We can express the present state of knowledge as a probability distribution, with probability in the Bayesian sense of 'certainty'. We can use a simple analytic function to describe a model of the state of knowledge, $P(<V)=0.5(1+\tan h(\log\{V-X\}/\log(W))$, where $P(<V)$ is the probability that the eruption rate is less than any value V. The choice of hyperbolic tangent is arbitrary and merely a matter of algebraic convenience – any curve with a logistic appearance would do; the formulation above exposes the parameters defining the distribution nicely. X is the nominal eruption rate of this model (in fact, the value at which our belief is 50% that the rate is lower) and W is the width of the distribution, which reflects the range of uncertainty. Ideally, after extensive observations we counted many eruptions and were able to state (for example) $X=0.4$ km^3/yr, $W=2$, which means we are 90% certain that the eruption rate lies between ~0.15 and ~1.1 km^3/yr. If we adopt an agnostic position that the eruption rate 'probably' lies between 0.01 and 10 km^3/yr, then a representative function has $X=0.13$ km^3/yr and $W=10$ (see Fig. 1). Clearly, the goal of observation is the reduction of W, the 'narrowing of the error bars'. Indeed, one might hope eventually to have enough data to use the formulation above without resorting to logarithms to accommodate the orders of magnitude of uncertainty! We note a broadly similar algebraic perspective in considering another poorly-constrained question, namely the likely longevity of human civilization (Gott, 1993).

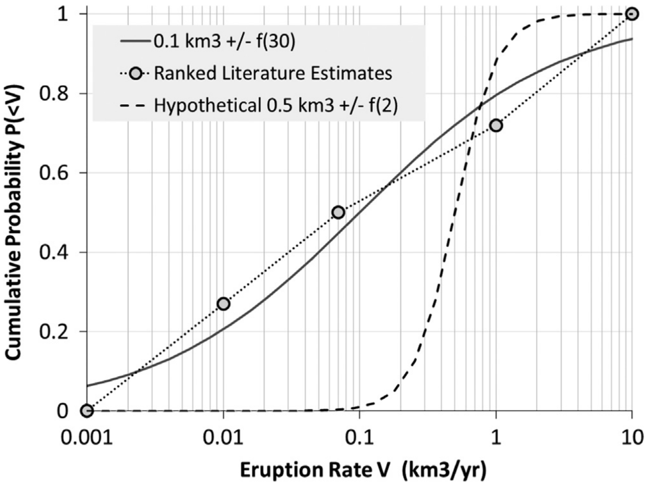

Fig. 1. Knowledge of Venus' volcanic eruption rate expressed as a probability distribution. Ranking literature estimates and extremes of 0.001 and 10 km^3/yr equally, we obtain (circles, dotted line) almost a straight line (indicating a uniform distribution of belief with the logarithm of eruption rate). The hyperbolic tangent formulation in the text with $X=0.1$ km^3/yr and $W=30$ (solid grey line) describes this state of ignorance reasonably well. With future data, one might hope to constrain the eruption rate to within a factor of 2 (e.g. dashed line), where the cumulative probability becomes closer to a step function.

We can, in a Bayesian sense, assimilate the literature estimates as discussed above, adopting values of 1, 0.07 and 0.01 km^3 for Philips, Strom and Crumpler, respectively. Without assigning any value judgements on these studies, we assign them equal weight and recognize that the real value is just as likely to be higher or lower; and then we can plot these as three points with cumulative probabilities $P(>V)$ of 75%, 50% and 25%, respectively. A function that describes these estimates is, as mentioned above with $X=0.1$ km^3/yr, $W=30$; we observe that we have made some notional progress, reducing W by a factor of several (while recognizing a low probability that all these estimates may be quite wrong).

We will revisit this means of portraying our state of knowledge in later sections.

3. Mt. Etna as a Venus prototype

Let us consider Mt Etna since its eruptive history is particularly well documented (e.g. Murray and Stevens, 2000). Over the 1879–1991 period, 24 major eruptions (Fig.2) of volume 0.001–0.3 km^3 with a total output volume of 1.6 km^3 were seen. Averaging 1.6 km^3 over total 1.1 centuries, the volumetric eruption rate of Etna is 0.015 km^3/yr; in other words, about a thousandth of the total terrestrial output or about equal to the minimum possible for Venus. These lava flows had a total area of ~74 km^2. Etna has a base area of ~1200 km^2 and a height of ~3.3 km, so its volume (modeling as a simple cone) is ~1300 km^3 (thus if no erosion occurred, it would take ~100,000 years to construct) Set in the context of a large number of eruption rates and volcano sizes compiled by White et al. (2006), Etna is modest in size but rather active (see Fig.3). Some Venus volcanoes are much larger, for e.g., Maat Mons (e.g. Robinson and Wood, 1993) has a volume (again adopting a simple cone shape, radius 200 km and height 5 km) of ~200,000 km^3. Analysis of Magellan data (Crumpler et al., 1997) indicate 167 large volcanoes on Venus >100 km diameter (thus >~1000 km^3 in volume) fairly comparable with Etna.