Venus: Satellite Orbital Decay and Consequent Crater Production

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Radar imagery of the surface of Venus has revealed the presence of nearly 1000 features identified as impact craters (1,2,3). It is generally supposed that the impacting material is derived from asteroidal and cometary sources (4,5,6), and that areal densities of craters can therefore be used, in conjunction with impactor flux estimates, to establish absolute exposure ages of regional surfaces (7,8,9). The slow, retrograde rotation of Venus and its present absence of natural satellites suggests an alternative source for impacting material (10,11,12): If Venus ever had any satellites, their most likely fate was tidal-induced orbital decay and eventual impact onto the surface of Venus. The purpose of the present study is to assess the feasibility of an extreme version of this scenario: can most (or even all) of the observed impact features on the surface of Venus be derived from satellitic material?

This hypothesis faces several problems: the mass problem (was enough mass available to produce the observed craters), the time problem (can satellites have remained in orbit until recently), the eccentricity problem (grazing impact of objects on circular orbits produce distinctive, elongate craters, contrary to observation), the inclination problem (objects in equatorial orbits would produce strictly equatorial craters, contrary to observation), the comminution problem (production of 1000 craters requires 1000 separate objects, unless they breakup sometime before impact). It will be seen that none of these problems represents a serious obstacle for the hypothesis. An important conclusion of this analysis is the cautionary note that, if the craters of Venus were mostly produced by orbital decay of former satellites, the areal density of craters provides no absolute age information at all. The crater distribution may all be as recent as the last significant satellite loss event.

The mass problem. Various scaling relations have been proposed linking crater diameter to energy and/or momentum of impactor (13,14,15). Assuming typical inner solar system impact velocities of 20 km/sec, a 200 km diameter crater requires a projectile with 20-30 km diameter. Satellite orbital velocity in a grazing orbit about Venus is 7.3 km/sec. Equivalent energy at this lower speed would require a projectile diameter larger by a factor (20/7.3)^2/3 = 1.96. It has been argued that only the normal component of impact velocity is effective in excavating the crater (16). In that case, the effective velocity will relate to orbital eccentricity. If the average normal velocity is 1 km/sec, the projectile diameter increases by 20^2/3 = 7.37 over the interplanetary scenario. In the energy scaling regime at fixed velocity, crater diameter is linearly proportional to projectile diameter. The cumulative size frequency distribution is bounded above by a D^-2 power law (2,3). As a result, the largest single crater represents a significant fraction of the total impactor mass. It thus appears that a single satellite of Venus with diameter of 200-300 km would contain enough mass to produce all the observed craters.

The time problem. Orbital evolution of a distant satellite would be dominated, over most of its history, by torques associated with tides raised by the satellite on the solid body of Venus. In that case the evolution of the orbital semimajor axis a is given by \( \frac{da}{dt} = F m a^{11/2} \), where m is the mass of the satellite, and F depends only on properties of Venus; specifically its mass M, radius R, Love number k_2 and tidal dissipation function Q. If F is constant, this expression can be integrated to yield

\[ a^{13/2}(t) = a^{13/2}(t_0) + (13/2) F m (t-t_0) \]

There are several important features of this solution. The rate of orbital evolution is very rapid at short distances and quite slow at larger distances, and is proportional to the satellite mass. The direction of evolution depends on the relative rates of planetary rotation and orbital revolution. For retrograde satellites (Triton), or prograde satellites inside the synchronous orbital distance (Phobos), angular momentum is transferred from the orbit of the satellite to the spin of the planet, and the orbit decays. At its present rotation rate, the synchronous orbital radius for Venus is 254 times the planetary radius. As a limiting case, consider that Venus has been slow and retrograde for 4.5 Ga. Then hypothetical satellites with mean densities of 3000 kg/m^3 and radii of (100, 200, 300, 400) km, starting from orbital radii of (14.2, 19.5, 23.5, 26.8) times the radius of Venus will be just now impacting the surface. All satellites that are larger, or started closer, will have already impacted.

The eccentricity problem. The history of orbital eccentricity variations during tidal decay of Venus satellite orbits is more difficult to reconstruct than is the semimajor axis history (17,18,19). The difficulty arises due to the more subtle interplay between angular momentum H and energy E in cases of variable eccentricity e. However, with few exceptions, the net effect of tides will be to decrease the eccentricity of those orbits for which the semimajor axis is also decreasing. Thus, we would expect that tidally evolved satellites will approach Venus with very small orbital eccentricities. During the later stages of orbital decay, long period and secular orbital variations due to interaction with the gravity field of Venus and third body perturbations from the sun can become important (20,21). The most important effect is associated with a variety of resonances through which the satellite will pass.
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The first important resonance to be encountered occurs when the apsidal precession period of the satellite equals the orbital period of Venus. The strength of that resonance depends on the orbital eccentricity of Venus. Thus, even if the satellite had exactly zero eccentricity prior to that resonance, it would evolve to a nonzero value. Other, shorter period resonances would be encountered as the satellite orbit evolved inward. The rate of eccentricity increase in these resonances does not depend directly on satellite mass. Thus, the limiting factor in how large an eccentricity can be produced is the competition between tidal decay and resonant excitation. Larger satellites will evolve across the resonant zones more rapidly, and thus have smaller eccentricities. Though details of this process have not yet been simulated, it appears that modest sized satellites (100-300 km radii) would impact the surface from sufficiently eccentric orbits that no bilaterally symmetric crater forms (as are diagnostic of grazing impact) would develop.

The inclination problem. The situation here is similar to the eccentricity issue discussed above. Tides will tend to damp satellite inclinations (17,18,24). The combination of dissipative and conservative torques acting normal to the orbital plane causes the orbit to precess, with a secularly decreasing inclination, about a reference surface. This so-called Laplacian plane coincides with the planetary orbit plane for distant satellites, and coincides with the planetary equator plane for close satellites. The transition distance, at which the satellite nodal precession rate equals the planetary spin precession rate (25), is 2.72 times the planetary radius. The expectation is that satellites would approach the planet with very small inclinations to the Laplacian plane. At sufficiently small distances, long period and secular orbital variations, with episodes of resonant enhancement, will increase the inclination. As with the eccentricity effect, smaller satellites will have more time in the resonant zone. It appears that modest sized satellites can acquire significant inclinations before impact. In addition, if the impacts are spread over $10^7-10^8$ years, tectonic processes within Venus will likely change the mass distribution enough to induce tens of degrees of polar motion. In that case, even if the impacts all took place near to the instantaneous equator, the entire surface could eventually be effected.

The comminution problem. It is clear that postulating an initially separate satellite as source material for each Venus crater will not present an attractive hypothesis. More likely is that a small number of larger satellites tidally evolved close to the surface and were then disrupted by a combination of tidal (26,27) and aerodynamic (28,29) stresses. A single rocky satellite with radius 200 km would be tidally disrupted into smaller fragments at a distance of 1.4 times the planetary radius. Further collisional comminution is quite likely. The subsequent tidal evolution of the fragments will be much slower than for the whole satellite, with the largest fragments evolving most rapidly. There is no particular difficulty in producing all of the separate impactors required to produce the observed population of craters on Venus, from a single satellite which was disrupted at 2400 km altitude, if it was in a reasonably high inclination orbit at the time.

Two key observations concerning Venus craters which support this hypothesis include: (a) the irregular distribution of craters, including relatively large areas essentially devoid of craters, and (b) the fact that very few craters are seen in states of partial destruction. A proposed explanation is that degradation processes work quickly enough to have removed all craters from other (interplanetary) sources, and that all of the observed population derive from a single, recent satellite decay-disruption-impact event. This explanation is correct, previous arguments about surface ages, resurfacing rates, and tectonic vigor need to be significantly revised.

References