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Doublet craters on Venus

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Abstract

Of the impact craters on Earth larger than 20 km in diameter, 10–15% (3 out of 28) are doublets, having been formed by the simultaneous impact of two well-separated projectiles. The most likely scenario for their formation is the impact of well-separated binary asteroids. If a population of binary asteroids is capable of striking the Earth, it should also be able to hit the other terrestrial planets as well. Venus is a promising planet to search for doublet craters because its surface is young, erosion is nearly nonexistent, and its crater population is significantly larger than the Earth's. After a detailed investigation of single craters separated by less than 150 km and "multiple" craters having diameters greater than 10 km, we found that the proportion of doublet craters on Venus is at most 2.2%, significantly smaller than Earth's, although several nearly incontrovertible doublets were recognized. We believe this apparent deficit relative to the Earth's doublet population is a consequence of atmospheric screening of small projectiles on Venus rather than a real difference in the population of impacting bodies. We also examined "splotches," circular radar reflectance features in the Magellan data. Projectiles that are too small to form craters probably formed these features. After a careful study of these patterns, we believe that the proportion of doublet splotches on Venus (14%) is comparable to the proportion of doublet craters found on Earth (10–15%). Thus, given the uncertainties of interpretation and the statistics of small numbers, it appears that the doublet crater population on Venus is consistent with that of the Earth.

Keywords: Craters; Impacts; Venus; Binary asteroids

1. Introduction

One of the more puzzling features in the terrestrial cratering record is the presence of doublet craters. These paired features form when two well-separated asteroids impact the Earth at nearly the same time and serve as evidence for the existence of a substantial population of asteroids with satellites (Bottke and Melosh, 1996a, 1996b). Melosh and Stansberry (1991) reported that three of the 28 large impact craters on Earth, $\geqslant 20$ km in diameter, are doublets. The Ries Crater and the Steinheim Basin of Germany are an association of a relatively large and small crater, 24 and 3.4 km in diameter, respectively, separated by 46 km. The Kamensk and Gusev craters of Russia, separated by only 15 km, are also represented by one large (25 km) and one small (3 km) component. The East and West Clearwater Lakes duo of Canada, separated by 28.5 km, is the most impressive doublet. Not only are the craters distinct, but also their diameters are also comparable (22 and 32 km). Melosh and Stansberry reviewed the literature and found that these terrestrial doublets are not chance associations; each pair shows evidence of having identical ages of formation (Melosh and Stansberry, 1991).

Doublet craters also exist on the Moon and Mars, but controversies still rage about their interpretation. Oberbeck and Aoyagi (1972) conducted a statistical analysis of martian doublet craters on the heavily cratered southern highlands. By examining Mariner 6 and 7 photographs and running a series of Monte Carlo simulations of random impact cratering, they argued that there was an excess of doublet craters relative to a random distribution. Similarly, a search on Mercury and the Moon yielded an excess of doublet craters (Oberbeck et al., 1977). Woronow (1978), however, countered this argument by creating a new Monte Carlo model that included the effect of varying crater size, which Oberbeck and Aoyagi's simulation had neglected. Woronow's model produced a random distribution that corresponded to the number of observed doublet craters (i.e., the excess doublet crater population was eliminated). Unfortunately, little

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work has been done since this exchange and the question of whether an excess of doublet craters exists on Mars, Mercury, or the Moon is still largely unresolved, although a study of the lightly cratered plains on Mars (Melosh et al., 1996) suggests a lower proportion than the Earth. This result agrees with theoretical studies of their formation by binary asteroids (Bottke and Melosh, 1996a).

Although doublet craters are observed on many terrestrial planets, little is known about their numbers, their sizes, and how often they are formed. A quantitative survey of these features is difficult to perform since most planetary surfaces are so heavily cratered that one cannot easily distinguish a chance association of two neighboring craters from a true doublet. Moreover, unlike the Earth, we cannot radiometrically date each crater to eliminate chance associations. For example, many craters have formed near one another on Mercury, the Moon, and Mars, but crater populations on these bodies are so dense that it is difficult to determine whether crater pairs are closely associated as a result of a double impact event or whether the association is simply one of chance. In the case of the Earth, the crater population is biased towards large craters and is both fragmentary and sparse (about 150 known craters), offering only a handful of doublet craters to examine. Even on Earth there is at least one chance association, that between Wanapetei Lake and Sudbury basin, which differ in age by about 1 Gyr.

A search for doublet craters on Venus avoids some of the problems associated with the other planets. Venus displays a much larger crater population (935) than the Earth, increasing the likelihood that doublet craters will be found there in greater numbers. At the same time, the number of craters is not so large that there is a high probability of chance associations. In addition, the entire surface of Venus is roughly the same age; approximately 500–700 Myr ago a resurfacing event eliminated all older craters on Venus (Strom et al., 1994, McKinnon et al., 1997). Finally, unlike the Earth, erosion on Venus' surface is nearly nonexistent. This uniformly young surface with negligible erosion maintains an exceptionally clean sample of the current population of impactors on Venus.

Unfortunately, the dense atmosphere of Venus greatly complicates quantitative investigation of Venus' cratering record. This thick atmosphere prevents small asteroid components from reaching the surface (McKinnon et al., 1997). This discrimination against small impactors biases the Venusian cratering record toward a smaller than actual number of doublet impact events, because the smaller component of each pair is more likely to be blocked from reaching the surface and thus recording its presence. Even for projectiles that do reach the surface, the atmosphere breaks up km-size incoming asteroids, producing strewn fields that may be up to 20-km wide (McKinnon et al., 1997; Phillips et al., 1991). We attempted to discriminate between such aerodynamically dispersed multiple craters and multiple craters caused by two distinct projectiles. Even smaller objects may not produce craters at all, but instead create circular radar-dark or bright features that are currently interpreted as airblast scars (Schaber et al., 1992; Zahnle, 1992). Because these so-called "splotches" may thus represent the traces of small impactors, we also survey them for evidence of double impacts.

2. Background: the origin of doublet craters

The existence of doublet craters on Earth implies that either a fraction of the asteroid population impacting the Earth are binary asteroids (Bottke and Melosh 1996a, 1996b; Pravec and Hahn, 1997; Richardson et al., 1998; Pravec et al., 2000; Margot et al., 2002; Merline et al., 2002) or that some instrumentality near the Earth is capable of pulling these objects into two components just before impact (Tanner, 1963; Aggarwal and Oberbeck, 1974). Of the latter, several such mechanisms have been proposed, but none is capable of explaining the observed doublets.

One apparently promising process, the tidal disruption of a binary asteroid during its final approach to a planet, was investigated by Melosh and Stansberry (1991). These authors numerically simulated planetary tidal stresses on contact binary asteroids approaching and impacting the Earth from a wide variety of initial orbital configurations. The results showed that planetary tidal forces could not significantly separate the Earth-approaching components, except for the few rare instances in which the components impacted at extremely low angles. However, the infrequent occurrence of low angle impacts and the lack of characteristic low angle morphologies, such as asymmetric ejecta blankets or an elliptical crater form in the known doublets makes this explanation very unlikely. These results have been corroborated by more sophisticated studies that modeled the tidal disruption of rubble-pile bodies (i.e., gravitationally-bound aggregates whose components are held together by self-gravity rather than physical strength; Richardson et al., 2002) using N-body codes (e.g., Asphaug and Benz, 1994; Richardson et al., 1998).

Another possible mechanism, atmospheric dispersion of an impacting asteroid, was examined by Passey and Melosh (1980). Numerical modeling demonstrated that aerodynamic forces are only capable of separating components by about 1 km in the Earth's atmosphere, far less than is observed for terrestrial doublets (see Appendix A). The largest doublets on Earth could thus not have been produced by either mechanism because their separation distance is too great.

The most plausible scenario for making doublet craters is to assume that a steady-state population of binary asteroids is constantly slamming into the Earth. Evidence for a substantial number of well-separated binary asteroids among the Earth-crossing asteroid population (15–17%) is supported by radar and lightcurve observations (Pravec et al., 2000; Margot et al., 2002; Merline et al., 2002). Numerical modeling results indicate this population could indeed produce the observed proportion of doublet craters on Earth ($\sim 10\%$; Bottke and Melosh, 1996a, 1996b).

Several physical mechanisms (e.g., collisions, tidal disruption, mass shedding via asteroid spin-up produced via the Yarkovsky/YORP effect; Merline et al., 2002; Bottke et al., 2002) may be capable of producing binaries, and it is not yet clear which one (if any) should dominate. Though a thorough review of this topic is beyond the scope of this paper, previous work has suggested tidal disruption alone may be capable of producing the observed fraction of binaries in the Earth-crossing asteroid population (Bottke and Melosh 1996a, 1996b; Richardson et al., 1998). In this circumstance, gravitational aggregates are gently pulled apart by tides during a close planetary encounter, leaving behind a pair of bodies on stable orbits (Farinella, 1992). This binary asteroid formation mechanism is similar, though usually less dramatic, to the one that produced the fragments of comet Shoemaker–Levy 9 (Asphaug and Benz, 1994). Using numerical models to simulate binary asteroid formation, orbital evolution, and doublet crater formation, Bottke and Melosh (1996a, 1996b) and Richardson et al. (1998) showed that a population of gravitational aggregates could be transformed by Earth/Venus tidal forces into a steady state population of $\sim 15\%$ well-separated binaries. These same models suggest that the fraction of binaries in the Mars-crossing asteroid population should be $\sim 5\%$ because Mars's density (and hence its ability to pull apart gravitational aggregates via tidal forces) is lower than that of Earth or Venus. Note that a population of this nature would produce 2–3% doublet craters on Mars. Interestingly, this prediction appears to be borne out by a survey of martian doublet craters (Melosh et al., 1996), which also predicts $\sim 2\%$ doublet craters. Thus, doublet craters potentially provide important constraints on the formation mechanism(s) of binary asteroids located in the terrestrial planet region.

In the remaining paper, we focus our attention on surveying Venus for doublet craters. Because the population of Venus-crossing objects is predominantly made up of objects that are or have been on Earth-crossing orbits (Gladman et al., 2000), we would predict that Venus, like Earth, should have $\sim 10\%$ doublet craters. As we will see, though, understanding the population of doublets on Venus is not straightforward.

3. Survey methods

3.1. Single craters

We used the crater data base of Schaber et al. (1995) to locate single craters as well as craters indexed as "multiple." Since there is a high probability of chance associations at great separation distances, the search was limited to single craters separated by 150 km or less. We used various criteria including degrees of brightness (radar backscatter cross section), overlapping ejecta blankets, and apparent angles of entry in classifying neighboring craters as "certain," "likely," "possible," and "unlikely" doublets. These classifications are outlined below. Each class is illustrated by figure of a clear example:

3.1.1. Certain

The characteristics of our "certain" doublets are: The ejecta blankets of the two craters

(a) display a similar degree of brightness,
(b) overlap one another, and
(c) indicate that the impactors came from the same direction.

The components of the "certain" doublet shown in Fig. 1, separated by 26 km, are 14 and 17.3 km in diameter. They have overlapping ejecta blankets of about the same brightness and are therefore roughly the same geologic age. The ejecta blankets are not circular or regular in shape but have parallel lines of bilateral symmetry. Likewise, the long axes of the elliptical craters are parallel. Therefore, we infer that the projectiles were traveling in the same direction and at the same rather low angle. The probability of such an association occurring by chance is negligibly small.

3.1.2. Likely

The characteristics of our "likely" doublets are: The ejecta blankets of the two craters

(a) display the same degree of brightness,
(b) overlap one another, and
(c) lack direction information.

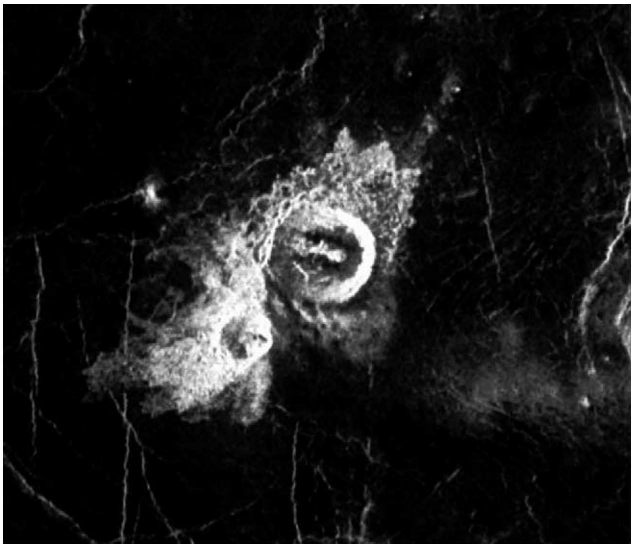

Fig. 1. "Certain" doublet found among single craters separated by < 150 km. The pair is separated by 26 km. The crater diameters are 14 and 7.3 km. The fact that both are rare, highly oblique elliptical craters, and that their elongation and ejecta blankets indicate approach from the same direction makes the probability of a chance association like this extremely small (Magellan image C1-45N117; crater locations are 46.75° N, 123.2° E and 46.55° N, 123.0° E).

Fig. 2. “Likely” doublet found among single craters separated by < 150 km. This pair is separated by 16 km and their crater diameters are 30 and 14 km. If either crater had preceded the other, debris from the ejecta blanket would have roughened (and hence brightened) the other’s crater floor, which argues that the impacts were simultaneous (Magellan image C1-15S043; crater locations are 19.5° S, 40.55° E and 19.55° S, 40.4° E).

We classified the crater pair in Fig. 2 as a “likely” doublet. The crater diameters are 30 and 14 km. The ejecta blankets overlap and exhibit the same brightness, suggesting that the impacts are associated. In addition, the small separation distance (16 km) between the two craters and the fact that both their floors are free of ejecta material, argues that the impacts were simultaneous.

3.1.3. Possible

The characteristics of our “possible” doublets are: The ejecta blankets of the two craters

(a) display the same degree of brightness,
(b) do not overlap, and
(c) lack direction information.

The craters of the “possible” doublet shown in Fig. 3 have diameters of 18.5 and 10 km, and are separated by 36 km. Both craters have ejecta blankets of about the same brightness, and thus are about the same geologic age. Both seem to have suffered some degree of atmospheric breakup of the impacting projectiles. However, the lack of obvious overlap relationships of the ejecta blankets makes it impossible to be certain they were created by the simultaneous impact of two projectiles. We can neither reject nor prove that the projectiles were paired in space.

3.1.4. Unlikely

The characteristics of our “unlikely” doublets are: The ejecta blankets of the two craters either

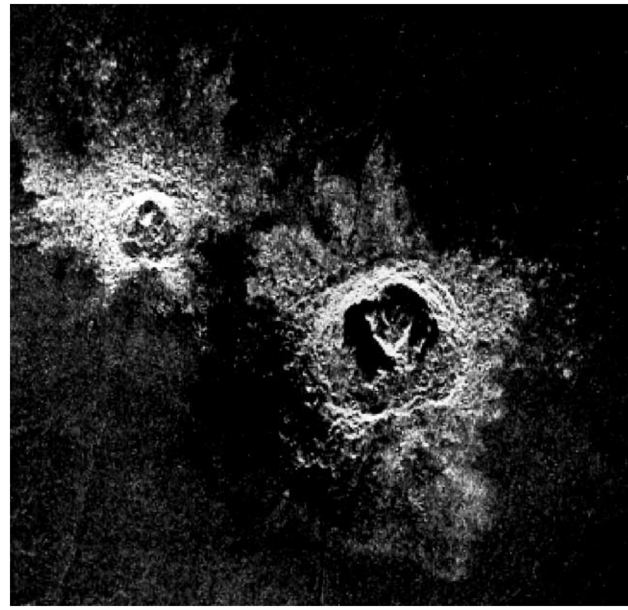

Fig. 3. “Possible” doublet found among single craters separated by < 150 km. This pair is separated by 36 km and their diameters are 18.5 and 10 km. Both craters have ejecta blankets of about the same brightness, and thus are about the same geologic age. The multi-lobed crater planforms are evidence for atmospheric breakup of the projectiles, as expected for craters in this size range. However, the lack of obvious overlap relationships makes it impossible to be certain they were created by the simultaneous impact of two projectiles. We can therefore neither reject nor prove that the projectiles were paired in space (Magellan image C1-30S171; crater locations are 32.7° S, 163.15° E and 33.0° S, 162.95° E). This doublet is associated with three airblast scars (Schultz, 1992).

(a) display different degrees of brightness,
(b) do not overlap one another, or
(c) indicate that the impacting asteroids came from different directions.

The craters of the “unlikely” doublet shown in Fig. 4 are 23.5 and 16 km in diameter and are separated by 117 km. Although the ejecta blankets are of comparable brightness, one appears to be the result of an oblique impact, while the other was a more vertical impact, which argues strongly against any association of the projectiles.

3.2. Multiple craters

Multiple craters are so closely associated that their rims overlap. The search for multiple craters was limited to craters having diameters greater than 10 km because, at smaller diameters, nearly all multiple craters are caused by atmospheric breakup (Herrick and Phillips, 1994). We used the same criteria described for single craters in classifying multiple crater associations as “likely,” “possible,” and “unlikely” doublets (none merited the classification “certain”). We classified the crater pair shown in Fig. 5 as a “likely” doublet, separated by 38 km. If the large crater (44-km diam.) impacted second, the small crater (4-km diam.) would have been obliterated. Conversely, if the small crater came

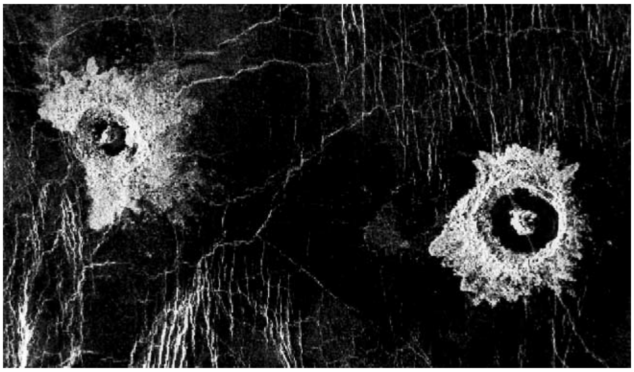

Fig. 4. "Unlikely" doublet found among single craters separated by < 150 km. This pair is separated by 117 km. The crater diameters are 23.5 and 16 km. Although the ejecta blankets are of comparable brightness, one appears to be the result of an oblique impact, while the other was a more vertical impact, which argues strongly against any association of the projectiles (Magellan image C1-45N286; crater locations are 45.55° N, 281.45° E and 45.35° N, 283° E).

Fig. 5. "Likely" doublet found among the multiple craters separated by 38 km (Johnson et al., 1991). The crater diameters are 44 and 4 km. The fact that the smaller crater is not obliterated by the larger one and the lack of a rim between the two argues that the impacts were simultaneous. The large separation makes it very unlikely that aerodynamic forces could have separated the projectiles (Magellan image C1-45S265; crater locations are 39.05° S, 260.25° E and 39.15° S, 260.70° E).

second, a rim between the craters would most likely be present, arguing that the impacts were simultaneous. The large separation distance makes it very unlikely that aerodynamic forces could have separated the two projectiles (see

Fig. 6. "Likely" doublet found among the multiple craters separated by 16 km. The diameter of the main, large crater is 18.0 km. If either crater had preceded the other, debris from the ejecta blanket would have roughened (and hence brightened) the other's crater floor, which argues that the impacts were simultaneous. The smaller projectile in this case seems to have been fragmented during atmospheric entry (Magellan image C1-00N266; multiple crater centered at 3.45° S, 265° E).

Appendix A). Figure 6 shows another "likely" doublet found among the multiple craters. The separation of the two components is 16 km. If either crater had preceded the other, debris from the ejecta blanket would have roughened (and hence brightened) the other's crater floor, which argues that the impacts were simultaneous. The smaller projectile in this case seems to have been fragmented during atmospheric entry.

3.3. Splotches

In the case of the circular radar-reflectance features called splotches, we examined the Magellan C-MIDR images of each splotch in the database of 402 light and dark splotches provided by G. Schaber and R. Strom (1995, personal communication). The database covers 87% of the surface of Venus. Unfortunately the database is incomplete because the Magellan images contain radar-dark portions on which dark splotches cannot be discerned, even though they may be present. Furthermore, as noted by Schaber et al. (1992), splotches seem to form preferentially in the lower-elevation regions of Venus. Splotches are thus not randomly distributed, a fact which we will try to take into account in our final analysis.

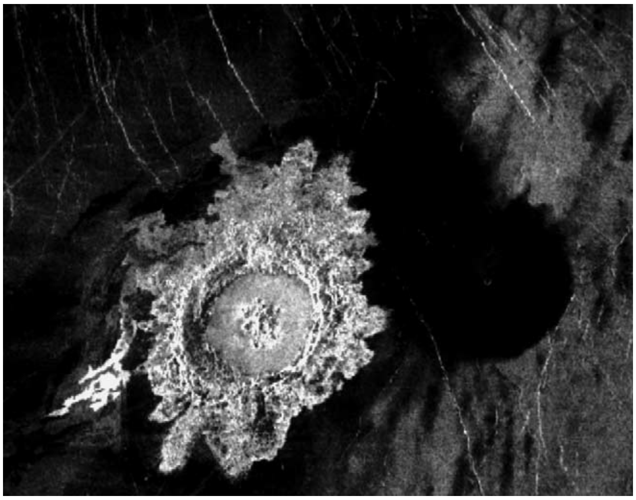

Fig. 7. "Likely" doublet found among the splotches separated by 70.5 km. The diameters of the splotch and crater are 47.0 and 41.7 km. The doublet consists of one large and one small component where the small component was not large enough to produce a crater (Magellan image C1-60N291; the splotch location is 59.4° N, 281.5° E). This splotch is listed in the database by Schaber et al. (1995). However, based on a topographic profile and the sharpness of the dark edge, the splotch may be a volcanic dome (P. Schultz, 1996, personal communication).

The criteria used to classify doublet splotches were less diagnostic than those used in the single and multiple crater associations. The lack of overlapping ejecta blankets makes it difficult to determine the relative ages of splotches, and the angles of entrance of the projectiles cannot be determined. Similarities between degrees of fading and splotch morphology were used to classify a doublet relationship as "likely," "possible +," "possible," "possible −," and "unlikely."

Since splotches fade with time, their degree of fading, or amount of degradation, can be used to qualitatively determine their relative ages. A faint, mottled splotch is assumed to represent an older impact event than a dark, sharply defined splotch. Splotch morphologies range from regular to highly irregular. Regular, or circular morphologies suggest a single impact event whereas irregular patterns could indicate a double or multiple impact event. This irregularity cannot be attributed to an irregular shape or heterogeneity of the impactor, because the splotches themselves are much larger than the projectiles that created them. Only a well-separated body striking near the site of the main impactor can substantially change the shape of the splotch.

"Likely," "possible +," and "possible" doublets display the same degrees of darkness and have splotch morphologies showing two distinct, circular patterns or an irregular pattern indicating a double or multiple impact event. "Possible −" and "unlikely" doublets display contrasting degrees of fading as well as splotch morphologies showing no evidence of a double impact event. We classified the doublet shown in Fig. 7 as a "possible +" doublet. Similar to the Ries/Steinheim crater pair of Germany, this doublet consists of a relatively large crater associated with a dark splotch. In this case, the dense atmosphere of Venus nearly prevented the small component from reaching the surface. However, the reader should be warned that P. Schultz (1996, personal communication) interprets this splotch as a volcanic feature, based on an altimetric profile and the sharpness of its edge. We classified the splotch pair shown in Fig. 8 as a "likely" doublet. The separation distance between the two impacting asteroids was large enough that two distinct circular dark patterns were formed.

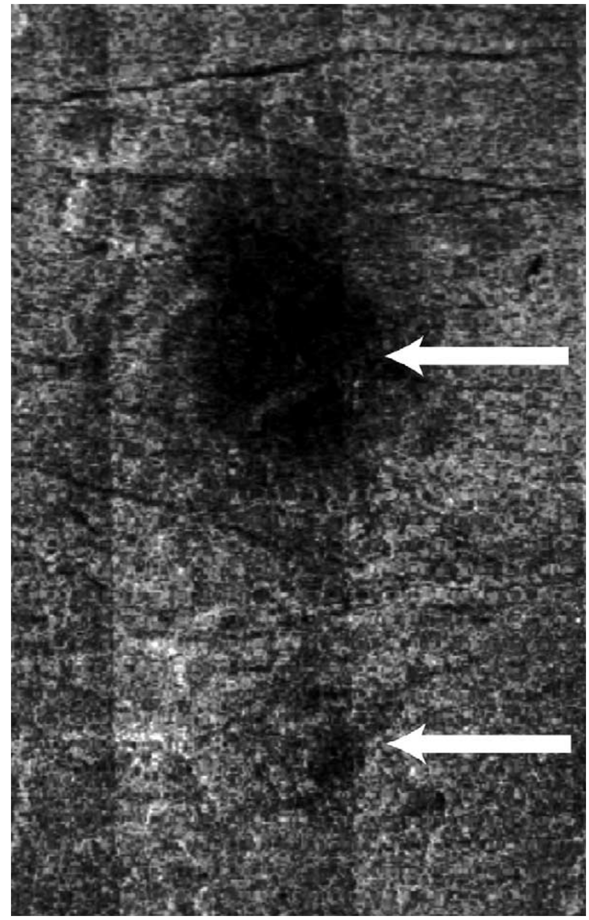

Fig. 8. "Likely" doublet found among the splotches separated by 38.3 km. The splotch diameters are 23.2 and 7.0 km. This doublet was formed by two projectiles < 2 km (Herrick and Phillips, 1994) in diameter whose separation was large enough to form two distinctive patterns (Magellan image C1-60N180; the splotch location is 59.8° N, 180.3° E).

4. Results

We counted the numbers of impact craters on Venus separated by less than 150 km and compared our results to the predictions of a model in which craters are randomly distributed over the surface of Venus. Our search resulted in the discovery of two nearly indisputable doublets among the adjacent craters, three among the multiple craters, and four among the splotches.

In the case of single craters, the total number of craters separated by less than 150 km was 58, of which 28 are possible doublets (those classified as “certain,” “likely,” and “possible”; Table 1: We omit pairs that are less likely to be doublets). Based on a calculation in which 935 points were randomly located on a sphere of the same diameter as Venus, the number of craters that should fall within 150 km by chance alone is 63 ± 8. Figure 9 compares the actual number of crater pairs on Venus to the average of five randomly constructed distributions as a function of separation distance. It is clear from this figure that there is no statistically significant excess of doublet craters on Venus compared to a random distribution. This does not mean that doublets do not occur: our two “certain” examples are clearly real doublets, but their numbers cannot be large.

Of 24 multiple craters greater than 10 km in diameter, 13 are possible doublets (those classified as “likely,” and “possible”; Table 2). We believe that for small separation distances, doublet or multiple crater associations are mainly the result of atmospheric breakup. However, Fig. 10 illustrates that there are a few possible doublets even at 30 km of separation, and their morphologies suggest a paired fall.

Table 1
Possible doublet craters separated by < 150 km

Latitude	Longitude	Diameter (km)	Separation (km)	Classification[a]	Comments
46.75	123.20	14.0	25.62	C[b]	c
46.55	123.00	7.3			d
−19.50	40.55	30.0	15.84	L[b]	e
−19.55	40.40	14.0			
−39.05	260.25	4.0	38.36	L[b]	
−39.15	260.70	44.0			
4.95	169.75	14.0	121.00	P	
4.95	170.90	10.0			
41.40	66.00	2.0	81.81	P	
41.10	66.95	12.5			
18.40	101.85	12.5	91.94	P	
17.90	102.60	19.0			
1.70	283.85	10.0	75.04	P	
1.15	284.30	22.5			
0.55	143.15	20.0	82.14	P	
0.00	142.60	6.0			
−22.00	342.70	16.6	86.43	P	
−22.50	343.40	5.9			
−27.15	114.85	10.0	61.96	P	
−27.25	114.20	4.5			
−32.70	163.15	18.5	36.31	P	
−33.00	162.95	10.0			
−73.90	195.30	4.0	84.92	P	
−74.70	195.00	8.0			
81.00	222.50	28.5	101.15	P	
80.95	228.60	4.5			
80.95	228.60	4.5	100.57	P	
80.00	229.00	7.5			
72.20	99.60	4.0	116.93	P	
71.10	100.00	10.0			
41.10	66.95	12.5	141.99	P	
40.60	65.30	2.0			
35.21	287.30	5.0	132.45	P	
34.55	288.60	16.0			
28.20	106.80	15.5	128.37	P	
27.80	108.10	8.0			
26.70	336.50	38.0	125.47	P	
25.60	336.00	13.5			
23.75	94.55	21.5	129.07	P	
22.60	94.10	2.8			
17.55	314.45	4.5	138.88	P	
16.70	313.40	6.5			
−5.10	31.35	16.0	148.96	P	
−6.40	30.80	13.0			
−12.40	307.40	10.5	149.57	P	
−12.42	308.85	15.0			
−13.00	272.55	25.0	145.09	P	
−13.40	271.20	20.0			
−26.10	168.95	10.0	116.79	P	
−26.50	167.80	3.0			
−30.30	248.30	21.0	100.30	P	
−30.30	249.40	10.0			
−57.85	250.50	18.0	122.46	P	
−58.70	252.00	22.0			
−63.50	56.50	14.0	143.19	P	
−63.75	59.50	27.0			
−64.20	232.20	12.0	128.11	P	
−65.10	234.10	10.0			
−65.10	234.10	10.0	147.92	P	
−66.50	234.20	8.0			
−67.00	241.80	9.5	148.64	P	
−68.25	243.50	11.5			

[a] C = certain, L = likely, P = possible.
[b] Pairs shown in paper.
[c] Rare, highly oblique elliptical craters. Ejecta blankets indicate approach from the same direction.
[d] If either crater had preceded the other, the debris from the ejecta blanket would have roughened and brightened the other's crater floor, arguing that the impacts were simultaneous.
[e] The large separation distance makes it very unlikely that aerodynamic forces could have separated the two projectiles.

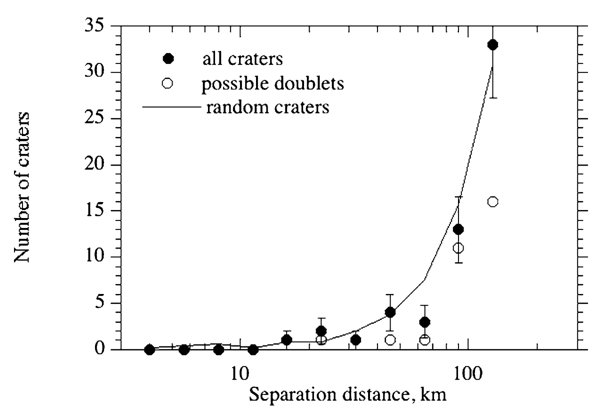

Fig. 9. Correlation between the number of craters per bin separated by 150 km or less (solid circles) and possible doublets (open circles) for given separation distances. The observed number of craters separated by 150 km or less (solid circles) is indistinguishable from the number that would occur by chance (represented by the curve), implying fewer than about 8 doublet craters on Venus were formed by simultaneous impacts. Error bars on the solid circles are 1 σ, computed from the number of craters N by the standard formula $\sqrt{N}$.

Table 2
Possible doublet multiple craters with diameters > 10 km

Latitude	Longitude	Diameter (km)	Separation (km)	Classification[a]
40.0	51.90	40.0	22.1	L
−3.45	265.00	18.0	15.9	L[b]
76.80	192.65	16.0	8.8	P
59.15	215.40	10.2	10.1	P
45.70	253.25	13.0	94.4	P
37.70	305.50	20.0	18.5	P
30.85	172.90	12.5	6.2	P
23.60	350.10	14.0	12.4	P
−6.75	334.10	12.0	6.2	P
−12.42	308.85	15.0	7.1	P
−15.30	84.90	10.5	5.3	P
−32.70	163.15	18.5	32	P

[a] L = likely, P = possible.
[b] Multiplets illustrated by figures.

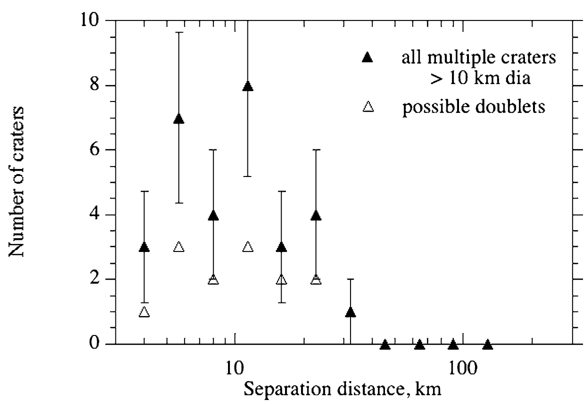

Fig. 10. Correlation between the number of multiple craters per bin having diameters > 10 km (solid triangles) and possible doublets (open triangles: note that error bars are omitted from these symbols to avoid overly cluttering the plot) for given separation distances. For small separation distances, we believe that most of the multiple craters are the result of atmospheric breakup.

Similarly, our splotch data was compared to a random distribution of impactors. The total number of splotches separated by less than 150 km was 108, of which 57 are possible doublets (those classified as "likely," "possible +," and

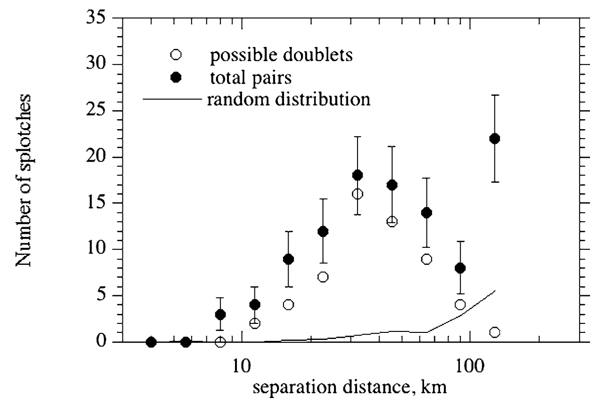

Fig. 11. Correlation between the number of splotches per bin separated by 150 km or less (solid circles) and possible doublets (open circles) for given separation distances. The number of observed pairs separated by 150 km or less (solid circles) is much greater than the number predicted by a random association (represented by the curve), implying that a significant fraction of splotches on Venus were formed by simultaneous impacts. Error bars on the solid circles are 1 σ, computed from the number of craters N by the standard formula $\sqrt{N}$.

"possible"; Table 3). We found only one crater/splotch association (and that one is somewhat questionable for reasons discussed above). The remainder of the possible doublets are splotch pairs. Figure 11 illustrates that the number of splotches occurring randomly increases as the separation distance increases. The observed number of splotches separated by < 150 km is much higher than the number occurring by chance. However, some care needs to be taken with this conclusion. Splotches are not randomly distributed on the surface of Venus, as discussed above. This non-random distribution manifests itself as a larger than expected number of pairs at any given separation. The number of crater pairs is thus about 4 times larger than expected for separations ranging from a few hundred km to about 2000 km. At larger separations the splotch separation distribution becomes indistinguishable from random. Since the number of pairs at a given range depends on the square of the areal splotch density, this is consistent with a distribution in which the splotches are absent from about half the surface area and

Table 3
Possible doublet splotches separated by < 150 km

Number	Latitude	Longitude	Separation (km)	Classification[a]	Comments
1	78.5	74	56.4	L	
18	55.2	346.8	41.16	L	Regular splotch separated from #19 by 41.16 km.
19	55	346.2	41.16	L	Regular splotch separated from #18 by 41.16 km.
70	38.7	344.1		L	
202	8.8	341.6	75	L	
279	−7.4	342.1	30.36	L	
14	59.8	180.3	38.29	L[b]	Diam. large splotch = 23.2 km. Diam. small splotch = 7.0 km.
218	5.1	255.2	37.5	P+	
224	4.1	5.8	28.57	P+	Complex splotch. Separation of main components is 28.57.
237	1.3	157.5	37.5	P+	
246	−0.5	312	42.86	P+	
248	−1.3	178.1	37.5	P+	

(*continued on next page*)

Table 3 (*Continued*)

Number	Latitude	Longitude	Separation (km)	Classification[a]	Comments
267	−4.6	27.5	21.43	P+	
322	−22.2	219.8	62.5	P+	
15	59.4	281.5	70.5	P+[b]	Association of one crater and one splotch. Diam. crater = 41.7 km. Diam. splotch = 47.0 km.
4	76.7	255.5	17.5	P	
7	63.4	333.5	51.0	P	
41	47.3	104.2	27.0	P	Small lobe on splotch indicates a doublet relationship, although parts are missing.
66	40	313.9	19 5.3	P	Two small splotches separated by 5.3 km. This pair is separated from a larger component by 19 km.
87	33.9	72.5		P	Large splotch cut by a tectonic feature.
99	30.8	47.1	23.68	P	
110	28.4	129.9	21.87	P	
131	21.7	249.3	26.79	P	
132	21.5	327.5	33.8	P	
134	21.4	325.8	35.71	P	
146	18.2	29.1	44.64	P	
147	18	51.5	38.29	P	
162	15	265.2	22.54	P	
175	12.8	264.3	17.86	P	
184	11.4	208	42.86	P	
187	10.4	165	62.5	P	Separated from #189 by 62.5 km.
188	10.4	268.7	53.57	P	
189	10.3	165.6	62.5	P	Splotch associated with #187. See comments for #187.
196	9.5	341.6	79.5	P	
199	9	193.5	48.21	P	
200	9	333.6	80.36	P	
203	8.7	333.7	83.93	P	
211	7	144.5	66.07	P	
214	6	276.9	35	P	
216	5.5	314.2		P	Elongated splotch; long axis = 33.9 km; short axis = 10.71 km.
225	3.8	273.1		P	Elongated splotch; long axis = 62.5 km; short axis = 29.46 km.
227	3.5	276.8	12.5	P	
230	2.9	155	30.36	P	
232	2.9	274.9	28.57	P	
234	2.4	209.4	39.29	P	
242	0.7	271.2	10.71	P	
243	0.6	178	21.43	P	
247	−1	270.7		P	Elongated splotch; long axis = 46.43; short axis = 37.5.
250	−1.7	148.7	37.5	P	
253	−2.1	162.5	16.07	P	
285	−8.5	319.7	53.57	P	Separated from #287 by 53.57 km.
286	−8.7	28.4	30.36	P	
287	−8.8	319.3	53.57	P	Separated from #285 by 53.57 km.
294	−11.7	200.1	16.07	P	
308	−17.1	267.2	28.57	P	
329	−23.8	17.9	39.29	P	
331	−24.5	44.1	30.36	P	
333	−24.9	153.2	39.29	P	
338	−26.3	74.7	155.36	P	
342	−29.3	159.5	35.71	P	
346	−33.3	161.9	89.23	P	Splotch associated with #347.
347	−33.5	163.5	89.23	P	Splotch associated with #346.
355	−36.8	33.2	22.32	P	
381	−45.9	103.1	26.79	P	
398	−69.4	120.1	53.57	P	
399	−73.6	302.1	107.14	P	Splotch associated with #400.
400	−74.1	301.1	107.14	P	Splotch associated with #399.

[a] L = likely, P+ = possible +, P = possible.
[b] Doublets illustrated by figures.

lie in randomly positioned patches a few 1000 km across. In spite of this background of larger than expected numbers of pairs, Fig. 11 shows that the number of observed pairs at separations of less than 100 km is more than 10 times higher still, indicating a tendency toward pairing over and above that imposed by the patchy, non-random splotch distribution.

Since splotches represent smaller projectiles, they should be more abundant than craters. However, there are only 402 compared to 935 craters, implying that the splotches fade with time. The splotches thus do not represent a complete sample of the last 500 Myr cratering record. Nevertheless, the statistical excess in the 10–100-km diameter range argues that a substantial fraction of these were created by paired projectiles.

5. Implications

If it is assumed that all of the "possible" doublets among the single craters are paired, then the proportion of doublet craters on Venus would be 4.4% = (28 "single" + 13 "multiple" doublet craters) / 935 total craters. However, since the observed number of doublets separated by less than 150 km (58) is indistinguishable from a random distribution (63 ± 8), we estimate that (at most) only 8 (one standard deviation $\sigma = \sqrt{63}$) of the "possible" doublets are paired (see Fig. 9). Adding these single craters to the 13 "possible" multiplet craters, we then find a proportion of 2.2% = (8 "single" +13 "multiple" doublet craters) / 935 total craters.

This proportion of doublet craters is significantly smaller than that found on Earth (3 out of 28). However, if the progenitors of doublet craters on Earth were subject to the same atmospheric screening present on Venus, only the Clearwater Lakes pair would have made a detectable doublet, yielding a doublet crater fraction on Earth of 3.5% (1 out of 28 craters). Therefore, the abundance of doublets on Venus (2.2%) would be comparable to that found on Earth (3.5%) if we compare similar size components.

The splotch population may be less biased by atmospheric screening. This population exhibits an overabundance of paired splotches in comparison to a random distribution. However, the problem with splotches is that they fade relatively rapidly, which may explain the presence of only one possible crater/splotch association (Fig. 7). We do not know whether small splotches fade more rapidly than large ones: If they do, then the observed number of paired splotches may be an underestimate of the actual number. It is thus difficult to compare the statistics of splotches directly with those of the craters. Ignoring these potential problems, we find that the proportion of all probable doublet splotches on Venus is 14% (57 out of 402), close to the proportion of doublet craters found on Earth (10–15%).

6. Conclusions

It is clear that doublet craters occur on Venus, although the Venus crater record shows a smaller proportion of doublets (2.2%) than that found on Earth (10–15%). Our best explanation for this disparity is that the dense atmosphere of Venus screens out the small members of true doublets (those less than 2 km in diameter). If the Earth had such an atmospheric screening effect, only one of its three known doublet craters would have been formed, making the proportion of doublet craters on Earth (3.5%) identical to Venus' (2.2%) within uncertainties. Small asteroids that do not reach the surface of Venus but leave short-lived circular splotches on the surface may give a better representation of the population of impactors. We find that the proportion of doublet splotches on Venus (14%) is comparable to the proportion of doublet craters found on Earth (10–15%). Therefore, we conclude that Earth and Venus were subject to a similar flux of co-orbiting asteroids, and that asteroid satellites must be common among both the near-Earth and -Venus asteroid populations.

Appendix A. Maximum aerodynamic separation of impactor components

As a contact binary asteroid or weak comet enters the atmosphere of a planet at velocity v it is subject to aerodynamic forces of magnitude ρv^2, where ρ is the ambient density of the atmosphere. These forces may either fracture the incoming projectile or separate a pre-existing fragment from the main mass. We here extend the arguments of Passey and Melosh (1980) to estimate the maximum separation these fragments may attain upon impacting the surface.

For simplicity, suppose the projectile follows a straight-line trajectory to the surface, inclined at an angle θ to the horizontal. If the components separate at height h_b above the surface, then the time of flight between separation and impact is $t_f = h_b / v \sin\theta$. The lateral velocity imparted at separation is due to the interfering shock wakes of the separating fragments. This force acts only during the time that the fragments are close to one another and is given by $\Delta v / v = \sqrt{3\rho/(2\rho_a)}$ (Passey and Melosh, 1980; Arteméva and Shuvalov, 1996), where ρ_a is the density of the asteroid. The cross range separation of the components s is thus $t_f \Delta v$, or

$$s = \sqrt{\frac{3\rho_0}{2\rho_a}} \frac{h_b e^{-h_b/2H}}{\sin\theta},$$

where H is the scale height of the (assumed) isothermal atmosphere and ρ_0 is the density of the atmosphere at the planet's surface. This function has a maximum for $h_b = 2H$, where the maximum separation is

$$s_{\max} = \frac{s_0}{\sin\theta} = \sqrt{\frac{6\rho_0}{\rho_a}} \frac{H}{e \sin\theta}.$$

Note that this is independent of the size or velocity of the incoming projectile. The scale factor s_0 has the magnitude 2 km on Venus, 150 m on Earth and only 18 m on Mars for stony bodies (density 3000 kg/m^3). Separations several times larger are possible for low angle entries (and atmospheric drag on the trajectories may also multiply separations by a factor of a few), but this gives an estimate of the degree to which aerodynamic forces can separate the components of an impacting asteroid or comet.

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