A CRATER CHAIN ON ENCELADUS: EVIDENCE FOR EXPLOSIVE WATER VOLCANISM

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INTRODUCTION. On Saturn's icy satellite Enceladus there exists a chain of craters extending roughly southward from the large crater Ali Baba. Ali Baba ("A" in Figure 1) is an irregularly shaped crater with a sharp rim crest, a very large central prominence, and a mean diameter of thirty-seven kilometers. The crater chain, to be referred to in this paper as the Ali Baba Chain (arrows in Figure 1), extends about 150 kilometers from the center of Ali Baba and is composed of about twenty craters or depressions, each about three to six kilometers wide and probably roughly 300 meters deep. The Ali Baba Chain is very nearly radial to Ali Baba and precisely describes an arc of a great circle. The simple geographic relationship held by Ali Baba with the Ali Baba Chain at first seems to indicate that the latter is a secondary crater chain associated with the former. However, other circumstantial evidence favors an endogenic origin:

(1) The Ali Baba Chain has approximately the same length, width, and depth as near-by structurally controlled grooves, suggesting a similar origin.

(2) The Ali Baba Chain is orthogonal to and apparently terminates against one of the grooves (lower arrow in Figure 1), and is parallel to Isbanir Fossa ("B" in Figure 1), again suggesting a tectonic control of some sort.

(3) Other crater chains and discontinuous groove-like structures are not obviously radial to any large crater.

Specifically, three possible origins must be considered for the Ali Baba Chain:

1. Secondary impact origin
2. Endogenic origin
   a. Tectonically controlled subsidence pits
   b. Tectonically controlled volcanic explosion craters

THE SECONDARY IMPACT HYPOTHESIS. Commonly cited characteristic features and relationships of secondary crater chains on the Moon, Mercury, Mars, and Ganymede include: 1) a radial relationship of the crater chain with a large, fresh, nearby primary crater, 2) the association with other radial crater chains and bright rays, 3) an elliptical plan view of individual craters, 4) a low depth : diameter ratio for individual craters, and 5) a "herringbone" interference ejecta pattern between closely spaced craters. Not all secondary chains display all of these characteristics. However, probably most secondary chains display at least one or two of them, and many display all five characteristics. The observation of herringbone ridges is especially revealing of an impact origin (Ref'c. 1). In the case of the Ali Baba Chain, however, the relatively low resolution of the Voyager imagery prohibits even a qualitative test for the last three of the five characteristics listed above, and perhaps for the second as well. Therefore, the origin of the Ali Baba Chain remains uncertain unless other quantitative discriminatory tests can be applied successfully.

Schultz and Singer (2) showed that secondary craters on the Moon, Mercury, and Mars do not have diameters in excess of a few percent of the diameters of their respective primaries. So the ratio of secondary diamecer to primary diameter ($D_s : D_p$) can probably be used as an aid in determining crater chain origins. Assuming the Ali Baba Chain is the largest secondary chain produced by the Ali Baba impact, then its value of $D_s : D_p$ can be compared with the values of $D_s : D_p$ for the largest secondary chains associated with other craters. Figure 2 is such a comparison for craters on the Moon, Mercury, Mars, and for a questionable secondary chain on Ganymede. $D_s : D_p$ is plotted against the appropriate ejection velocities for individual secondary projectiles. The latter values were calculated assuming a thirty degree ejection angle relative to horizontal, using the equations of Giamboni (Ref'c. 3). Any other angle could have been assumed and the qualitative results of this study would be unchanged. Figure 2 shows that over a wide range of ejection velocities the $D_s : D_p$ of the largest craters within the largest secondary chains rarely exceed 0.075. Because the Ali Baba Chain occurs in a cratered terrain with a background of unrelated, presumably primary impact craters, an allowance must be made. Crater frequency diagrams (4) show that up to about five craters larger than three kilometers in the Ali Baba Chain may be fortuitously superimposed primary craters. Even assuming the five largest craters are primary, it is clear from figure 2 that the Ali Baba craters generally appear to be too large to be secondary impact craters. These large values of $D_s : D_p$ probably require secondary projectiles that are considerably more energetic than we should expect relative to the energy of the primary impact. Alternatively, the near surface target material of the secondary projectiles might have a lower dynamic yield strength than the deeper target material of the primary Ali Baba impactor. This alternative seems unlikely for two reasons:

1. A significantly weaker surface layer some hundreds of meters thick should be revealed by an anomalously large population of small craters and a decrease in the slope of logarithmic crater size-frequency diagrams at some larger crater diameter; this apparently is not the case (4).

2. An active planet like Enceladus probably has a significant thermal gradient; this would tend to make the cold upper ice crust stronger than the deeper, warmer crust.

Figure 3 is a log-log plot of ejection velocity vs. primary crater diameter. There is considerable scatter in these data, and in fact this scatter would only increase if many different ejection angles had been assumed. However, the attempt here is not to probe deeply into the secrets held by secondary crater chains, but primarily to point out that by assuming a secondary impact origin for the Ali Baba Chain, anomalously low ejection velocities are implied. This would be true if any other ejection angle had been assumed. These data do suggest, however, that there is some positive dependence of ejection velocity on crater size. For craters the size of Ali Baba, secondary projectiles might be expected to have ejection velocities in the range 225 to 550 meters per second. Because escape velocity on Enceladus is just under 200 meters per second, all of the large crater-chain-forming projectiles should be expected to have escaped. Figure 3 suggests, at the risk of extrapolation, that the largest secondary chains on Enceladus should be very distantly associated with primary craters probably not more than twenty kilometers in diameter. Assuming typical values of $D_s : D_p$, these secondaries should not be visible on Enceladus; therefore, probably all crater chains visible in Voyager images of Enceladus are probably of endogenic origin.

An additional factor to consider are Coriolis forces. On the Moon, Mercury, and Ganymede, Coriolis deflections of ejecta streamers should be negligible except under unusual circumstances. Therefore, ejecta streamers tracing out simple ray-like paths (before gravitational arcing) will produce secondary crater chains along radial arcs of great circles. The Ali Baba Chain, however, should show a significant Coriolis deflection because of Enceladus' short rotational period and low gravitational accelerations, if the chain was produced by ejecta streamer particles all with virtually the same ejection azimuth. This apparently is not the case, since the Ali Baba Chain seems to lie on a great circle. Imprecisions in mapping and in estimates of the total mass of Enceladus at this time hinder a quantitative assessment of this argument.

Finally, crater counts show that Ali Baba is probably much older than the Ali Baba Chain. Ali Baba is probably one of the older features on Enceladus considering both its large size and the superposition of several craters over it, including the almost equally large crater Aladdin. The Ali Baba Chain is superimposed on a surface bearing approximately half the density of craters larger than seven kilometers relative to the area in and adjacent to Ali Baba (this author, unpublished data). In summary, four arguments weigh heavily against a secondary impact origin for the Ali Baba Chain:

1. The craters seem to be too large to be secondaries (Figure 2).
2. The inferred ejection velocities are probably too low (Figure 3).
3. The crater chain apparently shows no Coriolis deflection.
4. The crater chain is probably much younger than the presumed primary impact crater.

POSSIBLE ENDOGENIC ORIGINS. On the basis of available imagery it is impossible to argue conclusively either for or against the subsidence origin or the explosion hypothesis. Pit formation could occur by the subsidence of a thick layer of regolith or fine ice particles into a basement graben, or by the removal of liquid from a dike. Gravitational collapse of any sort is discouraged by the low gravitation on Enceladus (about 0.0079 g). Gas explosions, localized along a major structural discontinuity, are a more likely cause of the Ali Baba Chain. The gas explosion hypothesis carries with it the implication that Enceladus can generate vapor pressures in excess of lithostatic pressures. For an extreme range in likely surface density = 0.4 to 1.1 g cm^{-3}, a total vapor pressure in excess of 70 to 193 torr is required to overcome lithostatic pressure at a depth of 300 meters. The vapor pressure of pure H_2O at the triple point is only about 5 torr (5). If vapor explosions produced the Ali Baba Chain, a component more volatile than H_2O is required.

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Stevenson (Ref'c. 6) proposed that large troughs on several icy Saturnian satellites were produced by vapor explosions resulting from the interaction of an $H_2O\text{-}NH_3 \cdot H_2O$ eutectic melt with a clathrate of CH_4, Ar, or N_2. For example, he shows that a methane clathrate heated to 173° K by such a magma will generate a vapor pressure in excess of 100 torr. Another possible interaction, unmentioned by Stevenson, is that of water with the solid crystalline mix of water ice and ammonium hydroxide, which can generate an NH_3 vapor pressure in excess of 200 torr as the solid first melts at the eutectic and then warms to near 273 K as the heat of fusion is extracted from the water (based on P-X diagram in ref'c. 7). Whatever the interaction, if it occurs explosively it is likely to eject a combination of liquid droplets, vapor, and ice particles. The dominant phase in the explosion debris will depend on the circumstances. On low-g bodies such as Enceladus, this debris will likely be spread over the entire surface and into Saturn orbit, possibly forming structures such as the E-ring. In the case of water interactions with ammonium hydroxide + ice, H_2O will probably be far dominant over NH_3 (by mass) because the extremely high latent heats of fusion (8) and vaporization (7) of ammonium hydroxide ensures that a relatively large volume of water is required.

So far, infra-red spectral studies of icy Saturnian satellites have detected only water ice (9). This fact, coupled with the deduction that the E-ring particles probably condensed from a fluid phase (10), suggests that the dominant fluid phase involved in the explosions is probably water.

In conclusion, it appears that crater chains on Enceladus, and perhaps the continuous grooves, are best explained as structurally controlled gas explosion craters resulting from the interaction of water with ammonia-bearing ice.

REFERENCES

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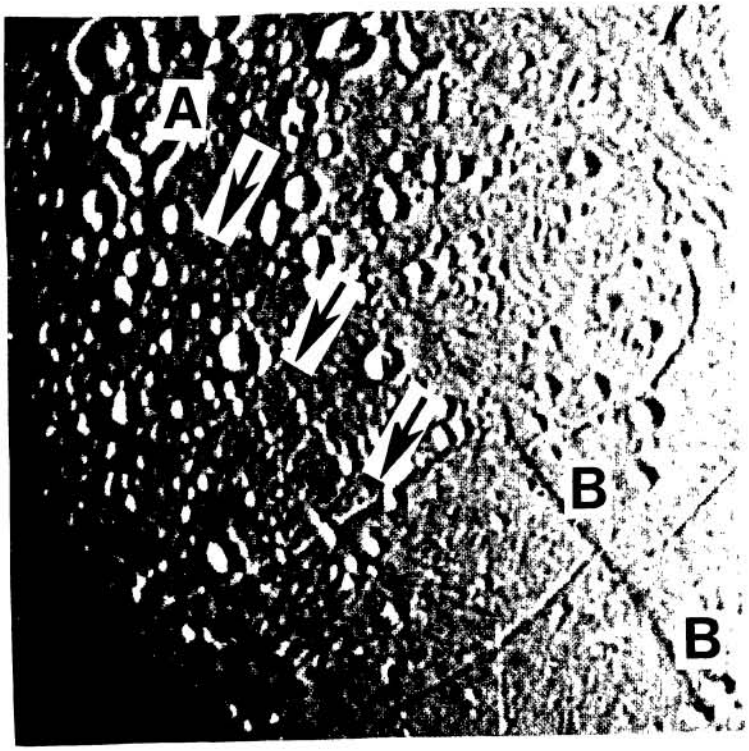

Figure 1 (right). Voyager 2 imagery of Enceladus. Features referred to in text.

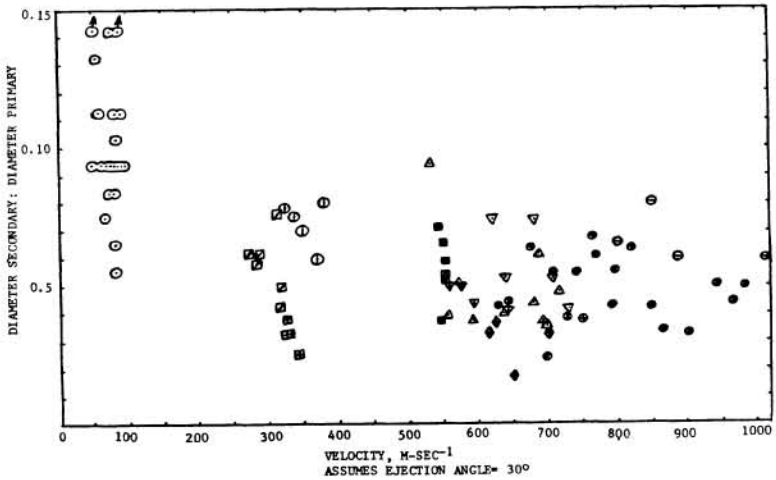

Figure 2 (below). Ratios of $D_s : D_p$ for primary craters and crater chains on Mercury, the Moon, Mars, Ganymede, and Enceladus. Symbols for crater chains associated with the following primary craters: ⊙ Ali Baba, 37 kilometers in diameter, Enceladus. ⊞ Aristarchus, 36 km, Moon. ⧄ Piazzi C, 40 km, Moon. ⦶ Un-named 68 km, 83.4° S., 164° long., Ganymede. ⊠ Copernicus, 96 km, Moon. △ Un-named, 48 km, 80.2° S., 262° long., Mars. ▽ Khansa, 110 km, Mercury. ⊕ Ahmad Baba, 125 km, Mercury. ◈ Tsiolkovsky, 180 km, Moon. ⊗ Verdi, 135 km, Mercury. ⊖ Strindberg, 190 km, Mercury. ⍒ Ts'ai Wen-chi, 110 km, Mercury.

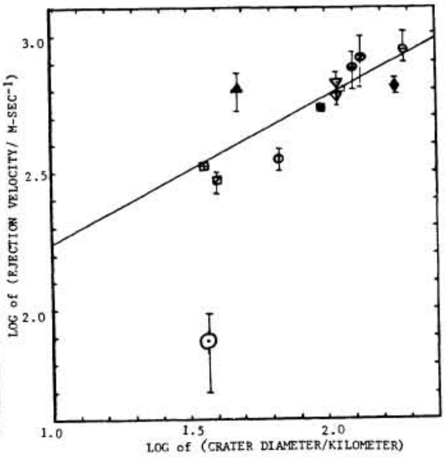

Figure 3 (bottom right). Inferred ejection velocities for secondary projectiles responsible for crater chains on Mercury, Moon, Mars, Ganymede, and Enceladus. Bars give ranges for most proximal and most distal craters in each crater chain. Symbols same as in Figure 2.