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SIMULTANEOUS IMPACT AND LUNAR CRATERS

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ABSTRACT

The existence of large terrestrial impact crater doublets and crater doublets that have been inferred to be impact craters on Mars suggests that simultaneous impact of two or more bodies can occur at nearly the same point on planetary surfaces. An experimental study of simultaneous impact of two projectiles near one another shows that doublet craters with ridges perpendicular to the bilateral axis of symmetry result when separation between impact points relative to individual crater diameter is large. When separation is progressively less, elliptical craters with central ridges and central peaks, circular craters with flat floors containing ridges and peaks, and circular craters with deep round bottoms are produced. These craters are similar in structure to many of the large lunar craters. Results suggest that the simultaneous impact of meteoroids near one another may be an important mechanism for the production of central peaks in large lunar craters.

In the past it has usually been assumed that impact of cosmic debris against lunar and planetary surfaces produces spacially and temporally random crater distributions. However, there is a considerable body of evidence that suggests that the impact process produces craters near one another at the same time. The Clearwater Lakes impact crater doublet, shown in Figure 1, is an example of two impact craters produced at the same time. One crater is 32 km in diameter and the other is 22.5 km in diameter. A detailed study of the Clearwater Lakes crater doublet has resulted in the conclusion that two large meteoroids impacted simultaneously near one another to produce the doublet members (1), and there is a possibility that the meteoroids could have been coupled together before entry into the atmosphere (2). The Ries Crater and the Steinheim basin are two other craters that have been considered to have formed at the same time (3). Many of the terrestrial crater fields have been considered by some workers to have been produced by swarms of meteoroids entering the Earth's atmosphere (4). There is now evidence of simultaneous impact on the planet Mars. A recent study of Mariner 6 and 7 photographs of Mars revealed more crater doublets than should have been observed if all craters were products of random single body impact events, yet there was strong evidence that crater doublet members were impact craters (5).

Observed Martian crater distributions were shown to be consistent with a meteoroid tidal fission model recently proposed (6). This model describes the relationship between tidal forces from the impacted planet or satellite and the stresses produced in a meteoroid that can split the meteoroid when stresses exceed the tensile strength. The analysis of splitting of a meteoroid due to the gravitational field of the impacted planet is important because it offers a mechanism for the production of paired meteoroids that is required in order to

explain terrestrial and Martian crater doublets and the mechanism leads to consideration of the simultaneous impact process. It has long been known that a planetesimal approaching a planetary body would break up due to the effect of the gravitational field of the larger body on the other; breakup occurring at a critical distance known as the Roche limit. However, until now, no consideration has been given to the types of craters that could be produced by simultaneous impact of the fission products at nearly the same impact point. The purpose of this paper is to present some preliminary results of a series of simultaneous impact cratering experiments and to show that the craters produced are similar in structure to many of the large lunar craters.

All experimental craters were produced by cylindrical projectiles of Lexan plastic that were bisected longitudinally to a point within 0.2 mm from the end of the projectile. Projectiles were launched normal to the fine grained quartz sand target at 2.3 km/sec and projectile spin imparted during launch by gun barrel rifling was sufficient to sever the small amount of material holding together the two halves of the projectile. Typically projectile separation at impact was about 6 cm for those projectiles launched with a gun barrel having one turn of rifling per 254 cm of gun barrel and about 4 cm separation for gun barrels having one turn of rifling per 330 cm of gun barrel. Except for one experiment, one impact occurred within five microseconds of the other impact. In this series of experiments the primary subject of investigation was the effect of variation of the ratio S/D where S is separation between impact points and D is the diameter of the craters produced by the projectile halves. This ratio is important because it varies for different conditions of impact on planetary surfaces (5) and this produces

craters with different morphologies. Individual crater size was varied by increasing or decreasing projectile length.

Figure 2 shows examples of craters produced under different conditions of projectile separation relative to crater diameter. When separation is large relative to crater diameter ($S/D = 1.3$, crater a) there is a subdued ridge perpendicular to a line connecting the center of one undisturbed crater with the other. When separation between impact is decreased relative to crater diameter ($S/D = 1.05$, crater b) individual crater rims are flattened and the ridge between craters is higher. For still smaller ratios of separation to crater diameter ($S/D = 0.81$, crater c) the individual craters begin to lose their separate identity. The ridge between the craters is wider but lower. Crater doublets characterized by S/D values less than 0.81 begin to resemble one crater rather than two. For example, crater d characterized by an S/D value of 0.44 is elliptical. Ridge development outside the crater is poor, but the ridge inside the crater is still quite well developed. When separation between impacting projectiles relative to crater diameter range from 0.36 to 0.0, crater geometry ranges from a single elliptical crater to a single circular crater. For example, crater e, characterized by an S/D value of 0.36, is elliptical and has a well developed central ridge. Crater f, characterized by an S/D value less than 0.36, is less elliptical and it has a flat crater floor that contains a well developed central peak. For still smaller ratios of S/D (crater g) the crater is circular and a series of straight ridges develop on the flat crater floor. There is no ridge development outside the crater. When projectiles are impacted at the same point, within 5 microseconds of one another, there is no central peak or flat floor. An example, crater h, is characterized by an S/D value of 0.0 and it has a deep round bottom. It

resembles a crater produced by one projectile. In summary, simultaneous impact of two projectiles in homogeneous targets produces doublet craters with central ridges that extend across the target surface, elliptical craters with central ridges, circular craters with central ridges and central peaks, circular flat floored craters with central peaks and ridges, and craters with spherical segment shape. The type of crater produced is dependent on separation between the projectiles relative to crater diameter. Some preliminary experiments have been performed where one projectile impacts behind the other. These results indicate that craters with central peaks and slump features on crater walls may be produced by near simultaneous impact events. For example, impact of a 0.24 gm projectile followed by a 0.43 gm projectile 25 ms later produces a crater with central peak and terrace like features on the crater wall. These result from collapse of the growing walls of the first crater as a result of the second impact.

Craters produced in the laboratory by simultaneous or near simultaneous impact of two projectiles are similar in structure to craters observed on the Earth, Mars and the Moon. The Clearwater Lakes crater doublet and doublets on Mars have already been compared to experimental craters (5). Craters produced in the laboratory by simultaneous impact can be compared to lunar craters. Figure 3 shows photographs of four of the craters produced by simultaneous impact and four lunar craters. The experimental craters represent a wide range in projectile separation. The existence of the lunar crater doublet (Plato K and Plato KA) near the Alpine Valley (crater b) is considered strong evidence for the existence of simultaneous impact on the Moon as well as Earth. It corresponds in every way with the experimentally produced crater doublet a. The presence of a ridge perpendicular to the bilateral axis of symmetry of the

doublet is characteristic of simultaneous impact. Both doublets appear to have been formed under similar conditions of separation between projectiles relative to crater diameter. The ridge associated with each doublet is equally developed. Crater d, the lunar crater Copernicus, has a flat floor and one long ridge and one short ridge on the crater floor. Crater c is a crater produced by simultaneous impact of two projectiles where the separation distance relative to crater diameter is small ($S/D = 0.36$). The experimental crater has a flat floor and three subdued straight ridges on the crater floor. In this regard, it is important to note that many of the lunar central peak craters actually contain straight ridges or ridge systems that are similar to those that are produced by simultaneous impact. Circular central peaks also occur such as that in the lunar crater Lansburg (crater f). Crater e, an experimentally produced crater with a central peak, is an analog for Lansburg. Both craters are characterized by a well developed central peak. Crater h, the lunar crater Wollaston, is bowl shaped and is similar to crater g, the experimental impact crater produced by simultaneous impact of two projectiles at the same place or by one projectile of twice the mass.

Simultaneous impact experiments using homogeneous targets have produced craters that resemble craters observed on the lunar surface. This, coupled with evidence for simultaneous impact on earth, is considered evidence that simultaneous impact of large meteoroids may have produced many of the lunar craters. There is additional qualitative evidence that supports this conclusion. It has long been known that there is a change in structure of lunar craters with diameters greater than 1 km (7,8). Preliminary measurement and classification of a large sample of craters on the moon's front side performed in this laboratory has documented this change of crater structure with size. The smallest of these

lunar craters are round bottomed. The frequency of these decreases as the number of flat bottomed craters increases. Central peak craters are more common for craters larger than the flat bottomed or round bottomed craters, and terraced craters, with and without central peaks, are most frequent in the largest crater classes. This change in crater structure with size resembles in some details the change in crater structure with size for lunar craters less than 400 meters in diameter. The structure of small lunar craters has been related to strength differences in the layered near surface structure of the maria (9). However, these layering effects do not control crater structure for craters larger than approximately 400 meters (9). Thus target properties probably cannot account for the structural differences observed in large lunar craters that are discussed in this paper. However, all of these crater types can be produced by simultaneous or near simultaneous impact of two projectiles in homogeneous targets. The mechanism of tidal splitting of meteoroids provides a mechanism for the production of paired meteoroids and this mechanism would also at this time provide a qualitative explanation of the observed change in lunar crater structure with size.

The theory of meteoroid fission by the tidal fission mechanism predicts that larger meteoroids break up at higher altitudes above the lunar surface than smaller meteoroids and the separation between impacting fragments on the moon's surface is greater for large meteoroids (6). Since crater size depends on projectile kinetic energy for impact craters (10), crater size is dependent on meteoroid size for a given impact velocity; the larger craters on the moon would as a rule have been produced by projectiles that are more widely spaced at impact than is the spacing for small craters. Consequently according to the experimental results presented in this paper and the tidal

splitting model we should expect the smallest craters to be round bottomed and the next largest to be flat bottomed. Still larger craters should contain central peaks. The observed change in lunar crater structure is from round bottomed to flat floored to central peaked, in qualitative agreement with that expected on the basis of the tidal splitting theory and the experimental results presented in this paper. A detailed quantitative check on the degree of agreement between the observed distribution of lunar crater types and those predicted by the tidal fission model is now in progress, but the qualitative results suggest a relationship between the predictions of the tidal fission model and the distribution of craters of different morphology. There may also be other as yet unknown causes for coupled meteoroids that could produce the observed crater types. However, any other mechanism must also explain the direct relationship between total meteoroid mass of the coupled bodies and separation at impact on the planetary surface.

The existence of the Clearwater Lakes craters shows clearly that simultaneous impact of meteoroids occurs. Experiments in the laboratory have shown that simultaneous impact of projectiles produces craters with structures similar to those of lunar craters. The most typical characteristic of craters produced by impact of projectiles very close to one another is the formation of a central peak or ridge. Therefore, some central peaks in lunar craters must have formed by this mechanism. However, other mechanisms have also been proposed for the formation of central peaks in lunar and terrestrial impact craters and they remain as valid possibilities.

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FIGURE CAPTIONS

Figure 1 - Dominion Observatory photograph of the Clearwater Lakes impact craters.

Figure 2 - Impact craters produced by simultaneous impact of two halves of a cylindrical projectile. S = separation distance between impact points; D = diameter of crater produced by $1/2$ projectile.

Figure 3 - Comparison of experimental impact craters and large lunar craters.



Fig. 1

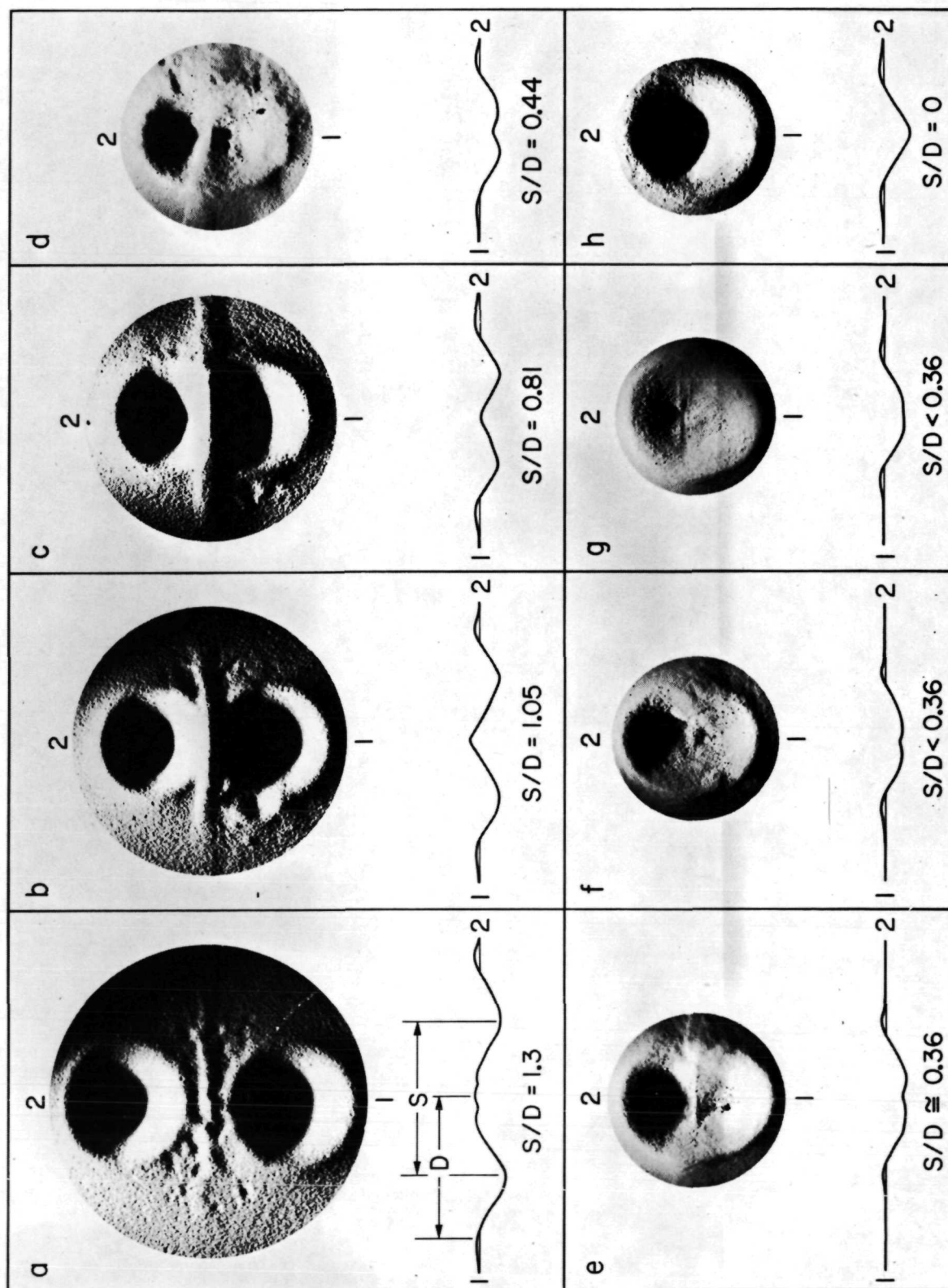


Fig. 2

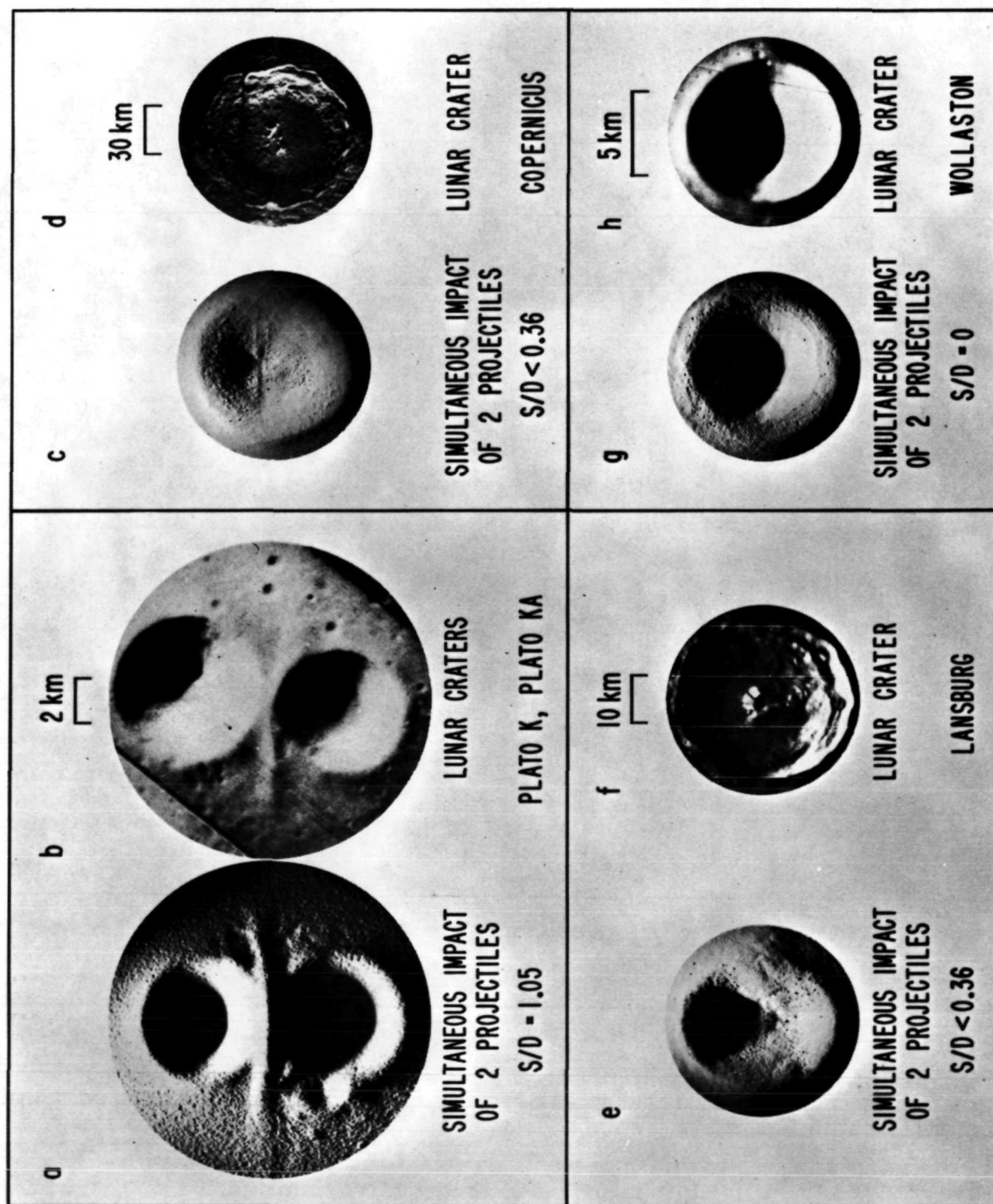


Fig. 3