PROCEEDINGS OF THE THIRTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE, PART 1
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 87, SUPPLEMENT, PAGES A84–A96, NOVEMBER 15, 1982

Grazing Impacts on Mars: A Record of Lost Satellites

PETER H. SCHULTZ AND ANNE B. LUTZ-GARIHAN

Lunar and Planetary Institute, 3303 NASA Road 1, Houston, Texas 77058

Grazing impacts can be identified on the basis of the elongate shape of the resulting crater and a distinctive pattern of ejecta deposits. Over 170 such impact craters larger than 3 km are recognized on Mars, and they represent more than 5% of the total crater population of the ridged plains. In contrast, the moon exhibits only one comparable example larger than 3 km on the maria, a frequency consistent with theoretical estimates for an isotropic influx of impactors. Many Mars grazers appear to occur along great circles. The most recent examples generally impacted in an east-west direction, whereas older grazers impacted in more northerly directions. We interpret the excessive number of grazers and the common impact directions as the result of satellites whose orbits tidally decayed with time. If all orbits originally had small inclinations similar to the orbits of Phobos and Deimos as well as the most recent grazers, then the change in impact direction with time can be explained as the result of shifts in the crust due to changes in the martian moments of inertia. The locations of the projected orbital axes (orbit-pole points) on the martian surface indicate that the geographic poles of Mars originally were situated at lower latitudes. More than 95% of the mass represented by these proposed satellites impacted prior to the emplacement of the volcanic plains of Lunae Planum. The estimated combined mass of grazing impactors would form a satellite at least 225 km in diameter. These results may provide new clues for the origin of Phobos and Deimos and perhaps the angular momentum of Mars.

INTRODUCTION

Most impact craters on the moon, Mars, and Mercury are relatively circular even though the most probable angle of impact is 45° [*Gilbert*, 1893; *Shoemaker*, 1962; *Gault and Wedekind*, 1978]. In a classic series of experiments, *Gault and Wedekind* [1978] showed that only low angle impacts (<10°) result in asymmetric distributions of ejecta and that only low angle grazing impacts (~5°) produce elongate crater shapes. On the moon and Mercury, we find very few craters larger than 5 km that display both the elongate shape and characteristic pattern of ejecta (e.g., the crater Messier). On Mars, however, there appears to be an excessive number of grazing impacts relative to nongrazing impacts—even after correcting for surface area and selection effects. We will conclude that Mars grazers most likely represent impacts by satellites whose orbits tidally decayed with time. This conclusion should have important implications for the origin and evolution of the largest surviving remnants, Phobos and Deimos, and may provide information about past shifts in the martian crust with respect to its spin axis.

The following discussions first establish the selection criteria used for identifying and classifying oblique-angle impacts. Second, we consider the distribution and orientation of Mars grazers. Third, we address the possible origins of Mars grazers as constrained by the observations. And fourth, we examine possible implications from our observations and conclusions.

SELECTION CRITERIA

Craters formed by oblique-angle impacts are identified on the basis of distinctive features revealed in the laboratory experiments by *Gault and Wedekind* [1978]. As the impact angle approaches 15° from the horizontal, the distribution of ejecta becomes asymmetric with a fan-shaped 'forbidden' zone uprange (toward direction of impact), whereas the crater shape in plan remains relatively circular. Smaller impact angles (~10°) result in a 'butterfly-wing' pattern of ejecta with the 'wings' perpendicular to the impact direction. In the laboratory, the crater shape remains relatively circular and becomes slightly elongate in the direction perpendicular to the impact direction. Grazing impacts (~5°) produce a pronounced 'butterfly-wing' ejecta pattern and an elongate plan along the impact direction. In addition, *Gault and Wedekind* [1978] observe a downrange ricochet component.

The crater Messier (14 km × 6 km) on the moon exhibits the elongate shape and 'butterfly-wing' ejecta pattern typical of the grazing impacts produced in the laboratory. The rim of Messier also changes elevation along its outline and resembles a saddle with low regions along the inferred impact direction [see *Schultz*, 1976], a morphology also revealed in photographs of experimental craters by *Gault and Wedekind* [1978]. Messier also contains a median ridge along the length of the floor. Although such floor ridges are not produced in the laboratory, they are characteristic of planetary-scale craters inferred to be products of grazing impacts on the basis of the other three features.

In our search for martian oblique-angle impacts, we limited our criteria to features characteristic of very low angles (<5°) in the laboratory as exemplified at broader scales by the lunar crater, Messier. These criteria, therefore, included: an elongate plan, 'butterfly-wing' ejecta pattern, saddle-shaped rim, and median floor ridge. Other craters exhibiting asymmetric ejecta patterns with 'forbidden' zones also probably represent low-angle impacts, but differential weathering and topography can easily mask or mimic the single selection criterion. Therefore only craters produced by grazing impacts (i.e., those meeting at least two of the four selection criteria above) were tabulated for this study.

Secondary craters are commonly elongate due to the angle of impact, the physical state of the projectile, and the number of impacting bodies [*Schultz*, 1981]. Because the present study is concerned with extra-martian objects, obvious secondary craters were eliminated on the basis of morphology. Large (3 km) secondary craters around the more recent major impacts such as Lyot typically do not exhibit the 'butterfly-wing' ejecta pattern

Paper number 2B1325.
0148-0227/82/002B-1325$05.00