CRATER CHRONOMETRY: EARLY HISTORY AND CURRENT ISSUES. William K. Hartmann[1], [1]Planetary Science Institute, 1700 E. Fort Lowell Blvd., Tucson AZ 85719.

Introduction: We humans have a perhaps a not-cosmically-unusual phenomenon at our disposal as an aid to unraveling the evolution of planets. Throughout the solar system, on all solid surfaces, nature is stamping out beautiful, circular formations at ultimately measurable rates, at scales ranging over 9 orders of magnitude from 10^{-3} m to 10^{6} m. Obviously, this phenomenon can help us interpret all sorts of planetary processes, from characteristic ages of lava plains, to timescales and size-scales of geologic processes such as fluvial erosion, aeolian deposition, exhumation, obliquity-induced climate changes, and surface modification by ice-related processes --- not to mention asteroid collision history and processes of primary and secondary cratering themselves. Many of these processes gradually accumulate at depth, allowing us to use the crater SFD to clarify their nature, topographic scales, and timescales.

Our generation is thus in the midst of developing a new field of “crater chronometry.” In spite of squabbles over techniques, the potential for this field is tremendous and, so far, insufficiently exploited.

History: The earliest study of the crater size-frequency distribution (SFD) known to the author was work by J. Young, who examined the SFD of lunar craters in 1940 in the journal of the British Astronomical Association [1]. Young used a list of 1300 measured crater diameters (and privately publishing a catalog of them in 1953). Fielder [2] in 1961, as well as Young [1] discussed the slope and shape of the SFD curve. They found that the portion of the curve at D $\lesssim$12-20 km had a shallower slope. During this period a debate still raged about whether lunar craters were volcanic or meteoritic, they used the SFD shap to debate origin processes of the craters. Shoemaker, Hackman, Eggleton [3], however in 1962, and Baldwin [4] in 1963, accepted the meteoritic hypothesis and began to use crater densities as a tool to establish stratigraphic and age relationships among lunar features.

During the 1960s, the author, along with some other currently active workers (C. R. Chapman, C. A. Wood) were students in G. P. Kuiper’s laboratory at the University of Arizona, and worked on a catalog of all craters of D > 4 km on the front side of the moon [5]. Hence, I began publications in this field as a graduate student. Early data on the power-law-like size distributions of asteroid and of meteorites were beginning to come in, and in 1964, I applied our new catalog data to refine the power law SFD, and used early scaling laws to show that if objects with the SFD of asteroids and meteorites were to hit the moon, the crater size distribution would be approximately as observed [6].

The 1960s saw two striking advances in crater SFD studies and chronometry. (1) Ranger 7 sent back photos during its crash-landing on the moon in 1964, extending the crater SFD down to sizes of a few meters. This allowed discovery of a “steep branch” of the SFD at D $\lesssim$ 2 km. The steep branch was shown (primarily by Shoemaker) to involve some proportion of secondary impact craters (not only from primary lunar impacts, but also from impacts on asteroids, which would also eject small secondary fragments, ultimately destined for lunar and planetary impacts). (2) Mariner 4, in 1965, photographed Martian crater populations at D ~ 10’s of km. Within months, Őpik [7, 8] noted that the SFD of those craters had a shallow SFD slope (closer to -1 than to the value -2 seen on the moon). He then noted that in the presence of a Martian crater obliteration effect proportional to crater depth --- such as infilling by aeolian dust deposition --- the SFD would be reduced in slope by unity. Thus the typical lunar slope of ~-2 on the plots mentioned above could be reduced to ~-1 on Mars, as observed.

Őpik’s work opened the door to use of crater SFDs to interpret planetary obliteration processes --- including some of the resurfacing processes seen on Earth. This aspect of crater chronometry, in my view, has the most potential for future development.

Measurements of Cratering Rate vs. Time: In 1965, the average contemporary terrestrial formation rate for large craters was constrained from Canadian shield data, and used to estimate that the lunar maria had age of “about 3.6 x 10^{9}” y [9]. It was then noted that the cratering rate has decreased since that era, and that “the decrease was rapid before the lunar maria formed and the flux has remained more nearly constant since then [10]. In 1966, those results were extended to reveal an “early intense bombardment,” such that the cratering rate in pre-mare time “averaged on the order of 200 times the post-mare average rate” [11]. These conclusions are still valid today --- regardless of whether a “terminal cataclysm” of bombardment occurred. It seems fair to characterize these results as early successful predictions from crater chronometry.

As soon as radiometric dates of Apollo and Luna rock samples were available, ca. 1970-75, Hartmann [12, 13], and Neukum [14] independently plotted crater densities vs. characteristic rock ages from the various landing sites, and showed that the flux must have been declining from ~3.9 to ~3.2 Ga, with a half-life of order 60-180 Ma, leveling out to a more constant rate after that. Fresh reappraisals of such data (such as [15], which confirms the high early flux) are to be encouraged

Current Issues: Secondaries: Development of crater chronometry was interrupted (in my view) by a dubious controversy in the mid-2000s about whether secondaries undermine the validity of crater chronometry. The criticisms were flawed, since some critics apparently assumed that the Hartmann and Neukum systems attempt to count only primaries, thus undercounting secondaries. However, as stated as early as 1967, we have “avoided so far as possible dividing craters by modes of origin” [16]. I.e., we count the total of primaries + non-clustered “field secondaries” [17]. Another critique was that the estimated formation rate of the youngest Martian ray craters is inconsistent with the crater chronometry system. An international team, however, examined a larger sample of ray craters with higher resolution images, and refuted this charge [18]. My sense is that the “secondaries” controversy, while involving important issues, is more or less moot.

Current Issues: Terminal Cataclysm (Late Heavy Bombardment): Starting in 1973-74 with dating of lunar samples by the Wasserburg group [19], and then supported by Ryder in 1990 [20], plus lunar meteorite data from Cohen, Swindle, and Kring in 2000 [21], plus early versions of the Nice dynamical model in 2005 [22], a hypothesis of intense “cataclysmic” bombardment in a 150 Ma period of ~3.9 Ga ago came to be accepted as an empirically proven fact. Hartmann, however, from 1975 onward, argued that no basin-forming impact “cataclysm” occurred, since no 150 Ma spike has been found in lunar or asteroidal meteorite impact melts [24]. Also, megaregolith production before 4.0 Ga ago would have preferentially converted pre-4.0 impact melt lenses, in the early upper few kilometers, to tiny clasts in upland breccias --- where they are indeed being found today [24, 25, 26]. Recently, Norman and Nemchin [26] and Swindle [27] have agreed that the classic idea of a 150-Ma spike in basin formation is “untenable” (N&N’s word). The classic “terminal cataclysm” (already being cited in theories of life’s origin [28]) may never have occurred.

Current Issues: Use of Small Craters: If we can identify the formation rate of small primary impact craters, we have a powerful tool for studying localized formations of kilometer scale. This process is underway, especially in the case of Mars, by Ingrid Daubar et al. [29]. A critique has arisen that the percent of primaries is not well known among the small craters, so that the observed primary production rate cannot be used to estimate ages. In answer, if we assume (temporarily) that all observed craters are primaries, and divide the observed density by the observed primary production rate, we have an upper limit on ages, which typically does not change gross conclusions about the 1st-order chronology, which we emphasize in crater chronometry. For example, we have shown that the upper 10 m of glacial structures east of Hellas date from the last few episodes of high obliquity a few 10^6 Ma ago --- which matches predictions of maximum ice deposition in just that area in just that period [30].

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