LUNAR IMPACT CRATERING: A BRIEF REVIEW AND PERSPECTIVE. H. Hiesinger[1], [1]Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, hiesinger@uni-muenster.de.

Introduction: Impact cratering is a multi-facetted field of research that spans from understanding the impact process to dating planetary surfaces, using multiple techniques. These techniques include, e.g., numerical modeling of the impact process, laboratory experiments, remote sensing studies of morphometric characteristics, geochemical and physical studies, impact flux modeling, and crater size-frequency distribution (CSFD) measurements.

Origin of lunar craters: For lack of a better understanding, early observers of the Moon considered its craters to be volcanic in origin (e.g., Hook, 1667; Schröter, 1791; Nasmyth and Carpenter, 1874; Suess, 1895), to be formed by burst bubbles of hot magma (e.g., Sacco, 1913), or tidal interaction repeatedly squeezing hot magma through fractures in solid plates to build the crater walls (e.g., Ebert, 1890). Even a formation of Copernicus crater as a coral atoll was proposed (Beard, 1925). Consequently, the origin of bright ray craters was linked to the deposition of drying salts that left a white efflorescence (Tomkins, 1908). In 1829, the German researcher Gruithuisen was probably the first to propose that lunar craters are in fact the result of impact cratering. However, while receiving some support, his findings were soon forgotten and although there were a few attempts to revive his idea (e.g., Proctor, 1873), it took until 1893, when Gilbert re-proposed the impact origin of lunar craters (Gilbert, 1893). Again, like Gruithuisen's, Gilbert's interpretation did not become widely known. In 1916, Öpik published a paper that came to the conclusion that lunar craters must have formed by explosions caused by high-velocity impacts of meteorites. This idea was supported by Ives (1919), Wegener (1921), and Gifford (1924). Finally, in 1942, Baldwin published his seminal paper "The meteoritic origin of lunar craters". However, only one year later, Marshall (1943) concluded that the igneous origin of lunar craters was the "true one" and that the "hypothesis of meteoritical impacts must be considered seriously challenged because of the failure to observe impact phenomena on the Moon today". Independent support for the impact origin of lunar craters was published by Dietz (1947), Urey (1952), Kuiper (1954), and finally in 1960, Chao et al. reported the discovery of coesite, a high-pressure polymorph of quartz which is still used today to identify terrestrial impact structures.

Dating of planetary surfaces: Once the impact origin of lunar craters was established, it was recognized that superposition criteria can be applied to their ejecta blankets to derive relative ages of geologic units and a stratigraphic system (e.g., Shoemaker and Hackman, 1962). Thus, Wilhelms (1987) was able to construct a moonwide relative stratigraphy using ejecta blankets of major impact craters as marker horizons. For example, only fresh craters with sharp morphology, such as Copernicus, exhibit bright rays, an observation used to define the Copernican system (e.g., Shoemaker and Hackman, 1962). Similarly, Fielder (1963) linked the darkening of a crater by the "destructive effects of ultraviolet light on the rock crystals" to the age of the crater. Another approach was taken by Boyce (1976) and Boyce and Johnson (1978), who used crater degradation to infer absolute ages of unsampled lunar regions.

Besides superposition, embayment, cross-cutting, and crater degradation, measurements of crater size-frequency distributions (CSFD) is suitable tool to decipher the stratigraphic relationships of geologic units. This technique is based on fundamental work by Öpik (1960) and Shoemaker (1962), followed by other researchers, including Baldwin (1964), Hartmann (1964, 1965), Chapman and Haefner (1967), Greeley and Gault (1970), Neukum and Dietzel (1971), CAWG (1979), and Neukum (1983). The general concept behind CSFD measurements is that an old surface that has been exposed to meteorite bombardment for a long period of time will accumulate more impact craters than a freshly exposed surface. Thus, by counting the number of craters and measuring their diameters, relative ages can be derived. However, two key assumptions must be made: (1) crater formation is a geographicallly random process, and (2) processes destroying the craters operate much more slowly than crater forming processes (McGill, 1977). McGillem and Miller (1962) showed that craters on the lunar surface are distributed randomly, whereas more recent studies, e.g., by Morota et al. (2008) and Le Feuvre and Wieczorek (2008, 2011) argued for nonuniform cratering of the lunar surface.

Neukum et al. (1975) and Neukum and Ivanov (1994) showed that lunar crater distributions measured on geologic units of different ages and in overlapping crater diameter ranges can be aligned along a complex continuous curve, the lunar production function (PF), which is given by an 11th degree polynomial. This was a major improvement over previous PFs, which followed various power laws, as those power laws were only applicable at specific crater diameter ranges (e.g., Shoemaker et al., 1970, Hartmann and Wood, 1971; Baldwin, 1971). No matter what PF is used, they allow relative ages to be derived for surfaces, even if they are not directly stratigraphically related. A major step forward in absolute dating was made when radiometric and exposure ages of Apollo and Luna samples became available (e.g., Tera et al., 1974; Nyquist et al., 2001 and references therein) and could be correlated with the cumulative crater frequency at a certain reference crater diameter for the sample locations (e.g., Hartmann, 1970; BVSP, 1981; Neukum, 1983; Strom and Neukum, 1988; Neukum and Ivanov, 1994; Neukum et al., 2001; Stöffler and Ryder, 2001; Stöffler et al., 2006; Geiss and Rossi, 2013; Robbins, 2014). With this correlation, known as the lunar chronology function (CF), it is possible to derive an absolute model age (AMA) for any unsampled region on the Moon. However, the calibration of the lunar chronology is not trivial. The frequency distribution of radiometric ages shows a range of ages for a given landing site and even for a single lunar sample due to an unknown combination of vertical and horizontal mixing (BVSP, 1981). Similarly, there are different view points on the selection and size of a proper count areas to best represent the landing sites and the samples collected from these sites. Selecting a count area that is not representative of the sample location will lead to an inaccurate CF, with consequences for dating unsampled surfaces. Thus, the correlation of crater counts with radiometric ages has been under debate for decades.

Current issues: *Chronology:* An issue under debate is the exact shape of the lunar CF. Stöffler and Ryder (2001) carefully reviewed the radiometric and exposure ages determined from returned samples; that is, they revisited the x axis of the lunar CF. Hiesinger et al. (2012a) and Robbins (2014), for example, investigated CSFDs of Copernicus, Tycho and North Ray crater, which are important calibration points for the CF at young ages. Thus, they revisited the y axis of the lunar chronology. Results of Hiesinger et al. (2012a) demonstrated that the cumulative number of craters counted on the ejecta blanket of North Ray and Tycho crater ejecta deposits are consistent with earlier measurements. However, for Copernicus crater and one of its rays, they found significantly lower cumulative crater frequencies than previous studies. Their new results for Copernicus crater fit the existing lunar chronology of Neukum et al. (2001) significantly better than the previous counts. Our AMA for Cone crater is ~39 Ma, which is in the range of model ages derived by previous CSFD measurements that vary between ~24 Ma (Moore et al., 1980) and ~73 Ma (Plescia and Robinson, 2011). Comparing the CSFD results to exposure ages of the returned samples (~25 Ma; Arvidson et al., 1975), we find somewhat older ages. Hiesinger et al (2000, 2003, 2011, 2012) also performed CSFD measurements of spectral units that contain the Apollo and Luna landings sites and found a good agreement between the derived AMAs and the respective radiometric and exposure ages of the samples. However, Robbins (2014) re-measured crater densities at all chronology tie sites and reported that there is a disagreement between his measurements and those used by Neukum et al. (2001) to construct the lunar chronology, such that if the classical Neukum chronology is used, certain model ages will differ by more than 1 Ga. As we use the lunar chronology to date planetary surfaces throughout the Solar System, independently testing these chronologies is of utmost importance.

Cataclysm: On the basis of radiometric ages of lunar impact breccias that show a pronounced peak at ~3.9-4.0 Ga, Tera et al. (1974) proposed that the Moon was hit by a particularly large number of projectiles during this time period. They termed this peak in impact rate the “lunar cataclysm” during which most of the large impact basins were supposedly formed. In the recent past, the cataclysm model has been tested with dynamic models, i.e., the “Nice model” (e.g., Morbidelli et al., 2001, 2005; Bottke et al., 2007). To explain the cataclysmic bombardment, these dynamic models predict drastic orbital changes of the large gas planets, in particular Jupiter that supposedly moved inward to disturb the asteroid belt and then outward again into its current position. Although this model appears plausible, it is still heavily debated whether the lunar cataclysm in fact occurred (e.g., Norman, 2009). A better understanding of the biased sample locations as well as detailed CSFD measurements of the South Pole-Aitken basin, which is the oldest basin on the Moon and such is an important anchor point for testing the cataclysm hypothesis, in fact do not support this model (e.g., Norman, 2009; Hiesinger et al., 2012b). Nevertheless, the question whether the cataclysm really occurred is one of the single most important questions that still await answers.

Outlook: With the onset of ever increasing spatial resolution imagery from recent lunar space missions it has become possible to study the lunar impact process and the chronology in unprecedented detail. Although these new data allow us to better understand the history and evolution of the Earth-Moon system, they also challenge some paradigms. Currently, we are in a situation where we have an excellent state-of-the-art global image data base necessary for accurate CSFD measurement but we still have to rely on a limited number of biased samples from the Apollo era to calibrate the lunar chronology. Thus, we need new age data from additional, previously unsampled, well understood regions to further improve the lunar chronology. As a next step in lunar exploration a lander for in situ dating of lunar rocks or, alternatively, a sample return mission should be considered by the international lunar community.

References: [1] Baldwin (1942), Pop. Astr. SO, 365; [2] Baldwin (1964) Astron. J., 69, 377-392; [3] Baldwin (1971) Icarus, 14, 36-52; [4] Basaltic Volcanism Study Project (BVSP) (1981), Pergamon, New York 1286pp; [5] Beard (1925), Pop. Astron., 33, 74; [6] Bottke et al. (2007) Icarus, 190, 203-223; [7] Boyce (1976), Proc. Lunar Sci. Conf., 7, 2717-2728; [8] Boyce and Johnson (1978), Proc. Lunar Planet. Sci Conf., 9, 3275-3283; [9] Chao et al. (1960), Science 132, 220; [10] Chapman and Haefner (1967), J. Geophys. Res., 72, 549; [11] Crater Analysis Working Group (CAWG) (1979) Icarus 37, 467-474; [12] Dietz (1947), Science, 105, 2715; [13] Ebert (1890), Ann. Phys. und Chem., 41 (277), 351-363; [14] Fielder (1963) Nature, 197, 69-70; [15] Geiss and Rossi (2013) Astro. Astrophys. Rev., 21, 54 pp; [16] Gifford (1924), New Zealand J. Sci and Technol 7, 129; [17] Gilbert (1893), Bull. Phil. Soc. Wash., 12,241; [18] Greeley and Gault (1970), Moon, 2, 10-77; [19] Gruithuisen (1829), Analekten Erd- und Himmels-Kunde, München, 2; [20] Hartmann (1964), Comm. Lunar Planet. Lab., 2, 197-204; [21] Hartmann (1965) Icarus, 4, 157-165; [22] Hartmann (1970) Icarus, 13, 299-301; [23] Hartmann and Wood (1971), Moon, 3, 3-78; [24] Hiesinger et al (2012a), J. Geophys. Res., 117, 10.1029/2011JE003935; [25] Hiesinger et al (2012b) Lunar Planet. Sci. Conf., 43, 1659; [26] Hiesinger et al (2011), Geol. Soc. Am., Spec. Pap. 477, 1-51; [27] Hiesinger et al (2003) J. Geophys. Res., 108, 10.1029/2002JE001985; [28] Hiesinger et al (2000) J. Geophys. Res., 105, 29239-29276; [29] Hook (1667) Micrographia; [30] Ives (1919) Astrophys. J., 50, 245-252; [31] Kuiper (1952), Proc. Nat. Acad. Sci. USA 40, Issue 12, pp. 1096-1112; [32] Le Feuvre and Wieczorek (2008), Icarus, 197, 291-306; [33] Le Feuvre and Wieczorek (2011), Icarus, 214, 1-20; [34] Marshall (1943) Pop. Astron., 51, 415-424; [35] McGill (1977), Geol. Soc. Am. Bull., 88, 1102; [36] McGillem and Miller (1962), J. Geophys. Res., 67, 4787-4794; [37] Moore et al. (1980) Moon and Planets 23, 231–252; [38] Morbidelli et al (2005), Nature, 435, 462-465; [39] Morbidelli et al (2001), Met. Planet. Sci., 36, 371-380; [40] Morota et al (2008), Adv. Space Res., 42, 285-288; [41] Nasmyth and Carpenter (1874), The Moon, New York, Scribner & Welford; [42] Neukum (1983), Habil. Thesis, Univ. of Munich, 186pp; [43] Neukum and Ivanov (1994) Hazards du to comets and asteroids, Univ. Arizona Press, 359-416; [44] Neukum and Dietzel (1971), Earth Planet. Sci. Lett., 12, 59-66; [45] Neukum et al. (2001) Space Sci. Rev., 96, 55-86; [46] Neukum et al. (1975), Moon, 12, 201-229; [47] Norman (2009), Elements, 5, 23-28; [48] Nyquist et al. (2001), The Century of Space Science, 1325-1376, Kluwer Academic Publishers; [49] Öpik (1916), Bull. Soc. Russe des Amis de l'Etude de l'Universe (Mirovédénié) 5, 125; [50] Öpik (1960), Month. Not. Roy. Astron. Soc., 120, 404; [51] Plescia and Robinson (2011) LPSC 42, 1839; [52] Proctor (1873), The Moon. Alfred Brothers, Manchester, England; [53] Robbins (2014), Earth Planet. Sci. Lett., 403,188–198; [54] Sacco (1913), Selenologie. In: Handwörterbuch der Naturwissenschaften, 9, p.7; [55] Schröter (1791), Selenotopographische Fragmente. 2 vols. Göttingen: Lilienthal & Helmst (1791-1802); [56] Shoemaker (1962), Physics and Astronomy of the Moon, New York, Academic Press, 283-359; [57] Shoemaker and Hackmann (1962), IAU Symp., 14, 289-300; [58] Shoemaker et al. (1970), Apollo 12 Prelim. Sci. Rep., NASA SP-235; [59] Stöffler et al. (2006), Rev. Min. & Geochem., 60, 519-596; [60] Stöffler and Ryder (2001) Space Science Rev. 96, 9-54; [61] Strom and Neukum (1988), Mercury, Tucson, University of Arizona Press, 336–373; [62] Suess (1895), Akad. d. Wissensch. zu Wien, 104, 21-54; [63] Tomkins (1908), Month. Not. Roy. Astron. Soc., 68, 571-574; [64] Tera et al. (1974), Earth Planet. Sci. Lett. 22, 1-21; [65] Urey (1952), The Planets: Their origin and development. Yale Univ. Press, 245 pp; [66] Wegener (1921), Tagesfragen aus den Gebieten der Naturwissenschaften und der Technik, 55, 48pp; [67] Wilhelms (1987), USGS Prof. Pap. 1348, 302pp.