REPORT ON THE *WORKSHOP ON ISSUES IN CRATER STUDIES AND THE DATING OF PLANETARY SURFACES*: SIGNIFICANCE TO LUNAR INVESTIGATIONS. L. R. Ostrach[1,2], S. J. Robbins[3], F. S. Anderson[3], N. G. Barlow[4], J. W. Head[5], J. B. Plescia[6] and the Crater Workshop Participants; [1]NASA Goddard Space Flight Center, Greenbelt, MD (lillian.r.ostrach@nasa.gov); [2]Oak Ridge Associated Universities, Oak Ridge, TN; [3]Southwest Research Institute, Boulder, CO; [4]Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ; [5]Department of Earth, Environmental and Planetary Science, Brown University, Providence, RI; [6]Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Overview: Impact crater populations are used to investigate numerous scientific questions, and the plethora of new data over the past several decades and the attempt to standardize techniques suggest that it would be very useful for the crater community to reexamine the best practices. Areas of consideration include understanding and analyzing impact craters, impact crater populations, how these populations and landforms evolve, and how we relate those findings to the broader planetary science community. The *Workshop on Issues in Crater Studies and the Dating of Planetary Surfaces* (called the "Crater Workshop" hereafter) was held 19–22 May 2015 at the Johns Hopkins University Applied Physics Laboratory in Laurel, MD. The primary goals for this workshop included discussion and improvement of community understanding of impact crater data and interpretations, and the application and use of statistical tools in the context of analysis of crater measurements to investigate various geologic, geophysical, and dynamical processes (e.g., derivation of surface ages).

The Crater Workshop consisted of plenary sessions that included invited and submitted talks organized by theme to stimulate discussion. These themes included historical approaches to crater investigations, new measurements using recent spacecraft data, effects of secondary crater contamination, and statistical approaches to better represent uncertainties and counting statistics associated with crater measurements. A cross-cutting, and little-appreciated, issue linking these themes is that incomplete knowledge of impactor flux, the keystone of all crater counting efforts, casts uncertainty on chronologic interpretations.

The following describes key findings and recommendations for LEAG and the greater science and crater counting community. In summary, significant focus needs to be placed on access and communication of the best techniques, statistical methods, contextual requirements, and error analyses for crater counting. Furthermore, gaps in our knowledge of impactor flux, and hence of the history of all bodies in the solar system, can only be remedied by acquisition of new well-provenanced dates from lunar terrains, both young and old.

Key Findings from the Crater Workshop:

1) Crater déjà vu: Numerous difficulties and problems related to crater investigations discussed at this workshop persist from earlier efforts. However, community memory of these issues tends to be short – many early efforts were published as "gray material" (e.g., Univ. Arizona LPL reports), and permanent archiving was not considered realistic (or necessary) until recently.

Recommendation: New review papers of current knowledge and outstanding questions could improve ongoing and future investigative efforts within the community by serving as a more long-lasting and accessible knowledge-base.

2) Community outreach: Common knowledge and accepted practices of experts in the cratering community, traditionally passed from mentor to student, is not necessarily described well in the literature nor is it always the case (e.g., a graduate student may embark on a crater study and their mentor may know as little as they do about crater studies). As a separate example, the crater community often inherently knows or acknowledges (mentally or orally) certain limitations. Such limitations, including uncertainties in measurement techniques, understanding that ages are *model* ages determined from an assumed impact flux with its own uncertainties, and the statistics, are not typically conveyed to colleagues or included in peer-reviewed publications. Improving communication between the crater community and the greater community would improve the quality of investigations.

Recommendation: The planetary science community would greatly benefit from educational opportunities (e.g., in-person and online workshops, in addition to new peer-reviewed publications) that present accepted "best" practices and techniques for crater-based investigations.

3) Not simply "crater counting": Crater-based investigations encompass a broad range of topics, and interpretation of these data must be informed by geologic context. For example, determining the age of a surface requires substantial effort beyond simply "crater counting," including identification of a single geologic unit, identification of possible secondaries, determination of the diameter at which the craters are in saturation (if they are), observations of morphologic variations among craters, and possible influences from target properties.

Recommendation: Future crater counting efforts must be informed by a robust background in geological science. The minimum requirements should be set out in a comprehensive review paper that can be referenced by all.

4) Statistics, computers, and standards should be welcomed: Estimates of statistical uncertainty are important in the interpretation of crater measurements; exploration of the advances in statistical (and computational) techniques over the past several decades may provide new understanding, improved interpretations, and more realistic estimates of uncertainty to crater-based data. As an example, the Crater Analysis Techniques Working Group published recommendations for measurement and presentation standards in 1979. However, that report remains as gold standard in the field and those original recommendations were limited by the inability to digitize adequate data at the time; modern computers eliminate the need for coarse binning and approximations. Furthermore, the cratering community should consider developing standardized training and calibration datasets for community use. In addition, investigations related to sampling (e.g., nested approaches, "largest" single craters and their associated processes, small surface areas), "repeatability" (same person conducting crater measurements on the same image) versus "reproducibility" (different people using the same image), and quantification of personal bias and potential sources of error are needed. To wit, these are also examples of inherent uncertainties that many in the crater community "know" of, but which are not conveyed to researchers outside the community.

Determining absolute model ages for geologic units is beneficial for physical models and construction of time-stratigraphic geologic histories (and so often are requested by colleagues who are not specifically crater analysts), but these absolute model ages are currently limited by uncertainties accounting only for count statistics. To develop better estimates of age, the current cratering rate needs to be better calibrated with observations of the Moon and Mars, better understanding of the production function, and a standardized method to calculate and report statistically realistic uncertainties for model ages.

Recommendation: The community needs crater counting standards and continued development and application of modern analytical and numerical statistical methods.

5) Need for additional dates from <3 Ga and 4+ Ga:

The Moon is the sole body in the solar system from which returned samples with known provenance exist, which is *the* key requirement to calibrating the lunar crater chronology. The lunar crater chronology is used to determine absolute model ages from crater measurements for not only geologic units on the lunar surface, but, by extrapolation, for nearly all other solid-surface bodies in the solar system. The rocks within the Apollo lunar sample suite constrain ages from 3.5–4.0 Ga well. However, well-provenanced samples spanning the range of ages 1–3 Ga do not currently exist, and until such samples are obtained, the chronology derived from returned lunar samples cannot be improved with any degree of certainty nor can existing uncertainties be reduced. Additionally, few samples are available from <1 Ga terrains (~3–5 distinct sites, samples are interpretations of material collected at the Apollo sites, not from the target to which they are attributed); furthermore, estimates of the very recent impact flux provide model ages that are alternatively younger or older, depending on the technique applied. Finally, the earliest history of the Moon remains uncertain, though the Decadal Survey has recommended a sample return mission to address these issues. These limitations result in up to 1 Ga uncertainties for the geologic history of the Moon and limit chronologies derived for other solar system bodies, e.g. Mars, Mercury, Venus, Vesta, and in models of early solar system dynamics. As a result, terrestrial bombardment between ~3.5 and 3 Ga, the period in which life may have arisen on Earth, may be twice the currently accepted rate, providing new insights about the habitability of the early Earth. Similarly, the era of liquid water on the Martian surface, intimately related to possible life on Mars, as well as the eras of voluminous volcanism on the Moon and Mars, might have ended ~3 Ga ago, or extended to as recently as ~1.7 Ga ago, requiring a major revision to our understanding of the formation of one-plate planets.

Recommendation: The only way to address these uncertainties is to obtain new age determinations on *lunar* rocks falling in the gap between covered ages. This requires, at a minimum, 3-5 or more samples/dates from large, uniform lava flows (optimal for crater counting) from multiple terranes, preferably addressing both age gaps (1–3 Ga, and 4+ Ga), and return of samples from ancient basin impact melt deposits, such as in the South Pole–Aitken basin.