DETERMINATION OF CRATERING RATES IN THE EARTH—MOON SYSTEM BY LUNAR SPHERULES; Timothy S. Culler, University of California at Berkeley Dept. of Geology and Geophysics, Berkeley, CA 94720; Richard A. Muller, University of California at Berkeley Dept. of Physics; Paul Renne, Berkeley Geochronology Center.

One of the primary goals of the Apollo missions was to provide information about the crater production rate on the moon, and hence on the Earth. Before the Apollo missions relative ages of different surfaces could be calculated by comparing the number of craters of a given size on the different surfaces. By returning samples from different lunar surfaces for radiometric dating, it became possible to attach absolute ages to different surfaces and to re-construct the cratering history of the early solar system. Our primary goal is to provide data about the crater production rates within the last 3 Gyr, although the method we propose will determine relative rates only, not absolute rates. We will do this by $^{40}$Ar/$^{39}$Ar dating glass spherules from random craters. Initially we will measure the ages of 30 to 40 lunar spherules; ultimately we would like to obtain the ages of several hundred to a thousand or more.

Interest in the recent terrestrial cratering record was piqued in 1980, when Luis and Walter Alvarez, Frank Asaro and Helen Michel published the hypothesis that the impact of a comet or asteroid on the Earth was the cause of the Cretaceous catastrophe, the mass extinction that killed over 50% of the Earth's life, including the dinosaurs[1]. The 'smoking gun' for this event has now been found, with the identification of the Chicxulub crater in the Yucatan as the site of the impact and its dating to precisely the time of the extinctions, to within 0.1 million years (Myr). The age was determined at the Berkeley Geochronology Center by $^{40}$Ar/$^{39}$Ar dating of individual glass spherules thrown out by the impact[2].

Furthermore, it is not known if this impact was an isolated event, or part of an intense period of impacts. Comet showers are brief periods of intense comet impacts predicted by J. Hills in 1981[3]. He showed that such a shower, bringing 10' or more comets into the inner solar system, would result if a star passed close to the Oort comet cloud. In 1984 we showed that the effect of a comet storm might be to give an illusion of an extended extinction period, perhaps accounting for the widely-held belief that the mass extinctions were extended in time rather than abrupt. A series of impacts taking place in a 1-million year period would give a series of extinctions, "stepwise," according to a later terminology, which if not recognized would look like a gradual extinction over the same period. Soon afterwards several extinctions were analyzed according to this model, and the stepwise extinction pattern was seen as consistent with the data.

In 1984, paleontologists Raup and Sepkoski analyzed the marine extinction data over the past 250 Myr and found a distinct periodicity of about 26 Myr[4]. Alvarez and Muller analyzed the cratering record on the Earth and found a periodicity of about 30 Myr[5]. However, plate tectonics and erosion obliterate all but a small number of terrestrial impacts so this result is somewhat ambiguous. If these periodicities exist and if they are linked, our views on the evolution of life would be profoundly affected.

As mentioned above, the terrestrial cratering record is not well preserved. The Moon, however, preserves craters much better than the Earth. This led to Hörz's suggestion that we sample the impact glasses from several hundred craters on the moon during another series of lunar exploration[6]. Our proposal is to analyze the glass spherules formed in impacts on the moon, which, while providing similar data, has the substantial advantage of not requiring further lunar missions. The second goal of our project, therefore, is to search for the presence of structure, such as peaks created by comet showers. One of the most interesting results that we can anticipate would be the discovery of clusters of impacts, perhaps one centered about 65 Ma, or 250 Ma at the time of the Permian-Triassic extinctions. Perhaps we could eventually see a series of such events, separated in time by the 26 Myr that Raup and Sepkoski have found in the mass extinctions on the Earth.

We believe that we can obtain these dates without going back to the moon by giving up the knowledge of which craters we have dated, and by measuring only relative cratering rates, not absolute.
Cratering Rates in the Earth—Moon System: Culler, T.S. et al.

Material from large impacts is thrown great distances; the rays from craters such as Copernicus and Tycho reach far across the face of the moon — this is reasonable, since typical impact velocities for comets are 30-45 km/sec, much greater than the lunar escape velocity of 2.38 km/sec. In our work with lunar soil, we have discovered 195 spherules in about 0.9 gm of lunar soil. The lunar spherules are expected to come from the cores of the impacts, and have some of the highest velocities of all the ejecta. Thus every gram of lunar soil could contain fragments from many, perhaps hundreds, of different craters.

A relatively recent improvement in radioisotope dating allows the time of the impacts to be measured with remarkable precision. For terrestrial samples younger than 0.1 Gyr, Paul Renne has obtained accuracies better than ±0.2 million years from single spherules. For the success of this project it is not necessary to duplicate such precision; indeed, accuracies of several million years will give important information on cratering rates. However one of the goals of this pilot project is to see what precision can be obtained with present equipment. Ar/Ar studies of lunar glass are further complicated by implantation of solar wind and cosmogenic Ar[7-9].

In this initial phase of the project we are trying to learn as much about the spherules as possible. We are taking scanning electron microscope pictures and electron microprobing all of the spherules recovered from the soil sample. We plan to date the first 14 spherules we have finished analyzing with the SEM and electron microprobe to determine the quality of the dates that we can obtain using $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{37}\text{Ar}/^{38}\text{Ar}$ cosmic ray exposure age dating. In the second phase of this project we will choose approximately 20 spherules to date, based on their dissimilarity from each other. We would like to find 20 spherules from 20 separate craters. Ultimately we may have to reject (as likely from the same impact) any two spherules with similar ages that do not have sufficiently different chemical compositions. Several elements, including titanium, appear to vary significantly across the lunar surface. From physical appearance and microprobe analysis we will select spherules that are relatively young, different from each other, and originate from impacts rather than volcanic events. We hope to be able to identify spherules formed by different impacts by comparing the concentrations of elements (like titanium) in the spherules. We attempt to distinguish between impact and volcanic spherules in several ways. The absence of schlieren and rock fragments, high volatile concentrations and high Mg/Al ratios are all indicative of volcanic glasses. We have also chosen samples from the maria to de-emphasize the heavy bombardment that took place prior to the flooding of the lunar plains. In addition, if we chose spherules with highland composition, we are more likely to find spherules from non-local sources (and therefore we are more likely to find spherules from different craters). Furthermore, highlands spherules found on the maria are likely to be younger than the maria they are emplaced on unless they were transported to their location on the maria without having their radiometric clock reset. Other chemical and geophysical methods for distinguishing recent spherules will be considered.