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LARGE IMPACTS AND CLIMATIC CATASTROPHES ON THE EARLY EARTH;

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Radiometric dates of cratered lunar surfaces suggest that the cratering rate on the ancient Moon was substantially larger than the present rate before about 3.2 Gyr. A fit to this data suggests that the cumulative flux $N_{cum}(m)$ of impactors of mass m can be adequately represented by the expression $N_{cum}(m) = a[1+Be^{-\lambda(t+4.6)}]m^{-b}$, where $a = 1.55 \times 10^{-23}$ $kg^{b}m^{-2}sec^{-1}$, $b = 0.47$, $B = 2300$ and $\lambda = 4.53$ Gyr^{-1}. Since the cratering rate was higher than present on the Moon, it seems likely that it was similarly higher on the Earth. It is thus gratifying that Lowe and Byerly (1) have recently reported the occurrence of beds of spherules up to 2 m thick in 3.2 to 3.5 Gyr old Archean rocks. These spherule beds closely resemble the 3 mm thick spherule beds associated with the K/T boundary (including elevated iridium abundances), widely believed to have been deposited in association with the impact of a 10 km diameter comet or asteroid.

Until recently it was believed that the spherules at the K/T boundary were transported worldwide as windblown dust. However, it is clear from the 0.1 to 1 mm diameter reported for the bulk of these spherules that their atmospheric residence time is very short, only a few hours, leaving ballistic transport as the only viable means for their global dispersal. We have argued previously (2) that when ballistically transported spherules and other debris reenter the atmosphere approximately 1/6 of their total energy is converted to thermal radiation on the Earth's surface, whereas about 1/3 is deposited in the atmosphere itself, absorbed by water and CO_2. In the case of the K/T impactor the energy irradiating the Earth's surface was about 10 kW/m^2, and the adsorbed energy was capable of raising the average temperature of the lower atmosphere by about 10°C. This amount of thermal radiation is just capable of causing spontaneous ignition of the Cretaceous forests, thus explaining the soot and charcoal found in the boundary clays (3), but the temperature rise of the lower atmosphere is not sufficient to alter its overall stability (the potential temperature difference between the surface and the stratosphere is between 100° and 140°, depending on latitude(4)). On the other hand, the reentering debris would have been relatively efficient at producing NO. Using an estimated efficiency of NO production of one molecule/ 40eV of energy deposited, or 7×10^{-9} kg of NO/Joule (5), the ejecta from the K/T impact may have produced 1-3.5 kg of NO/m^2, or NO concentrations of 100-350 ppm. The low Ph caused by such an increase in NO has been suggested (6) as potentially responsible for major oceanic as well as terrestrial extinctions.

The spherule beds in the Archean rocks, however, suggest still greater climatic perturbations. Since thermal energy generation scales directly as the mass deposited, a 10 cm thick spherule bed, if deposited ballistically over the entire Earth, implies thermal irradiation powers of roughly 300 kW/m^2 for periods of time of about an hour (the time scale for deposition is the same for large and small events), temperature rises in the lower atmosphere approaching 300°C, and NO production approaching 1% of the total atmospheric mass (assuming that the ancient Earth's atmosphere was similar in density and structure to the present atmosphere). Surface temperatures on rocks or soil would have approached 1000 to 1700°C, the temperature of the radiating ejecta in the upper atmosphere. It seems unlikely that any life could have survived the thermal pulse on the surface, although oceanic life would have been protected by the evaporation of a few tens of cm of water. The rise in overall atmospheric temperature would have been sufficient to overturn the atmosphere, mixing the suddenly heated troposphere into the stratosphere on a time scale of a few hours. After this sudden event further climatic perturbations may be expected to have continued for some time, perhaps years. Using the equation for the impact cratering flux on the Moon given above, an impact of this magnitude should occur roughly once every 150 Myr on the Earth. The 2 m thick spherule beds imply corresponding greater, although rarer, catastrophes.

The early Earth thus appears to have been a violent and rather inhospitable place: The recent detailed study of the K/T impact has shown that the climatic perturbations of large impacts appear to be more profound than previously estimated. Although ideas similar to this have been previously suggested (7) for very large impacts, we argue here that even the smaller events recorded by ejecta layers in Archean rocks probably played an important role in shaping the environment of the early Earth, and thus the environment in which life arose.

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