Impact production of NO and reduced species K. Zahnle, J. Kasting NASA/AMES, MS 245-3, Moffett Field, CA 94035, and N. Sleep, Dept. of Geophysics, Stanford.

It has recently been suggested that a reported spike in seawater $^{87}Sr/^{86}Sr$ at the KT boundary is the signature of an impact-generated acid deluge[1]. However, the amount of acid required is implausibly large. Some $\sim 3 \times 10^{15}$ moles of Sr must be weathered from silicates to produce the inferred Sr spike[1]. The amount of acid required is at least 100 and probably 1000 times greater. Production of 3×10^{18} moles of NO is clearly untenable. The atmosphere presently contains only 1.4×10^{20} moles of N_2 and 3.8×10^{19} moles of O_2. If the entire atmosphere were shocked to 2000°K and cooled within a second, the total NO produced would be $\sim 3\times10^{18}$ moles. This is obviously unrealistic. A (still too short) cooling time of 10^3 sec reduces NO production by an order of magnitude. In passing, we note that if the entire atmosphere had in fact been shocked to 2000°K, acid rain would have been the least of a dinosaur's problems.

Acid rain as a mechanism poses other difficulties. Recently deposited carbonates would have been most susceptable to acid attack. Strontium liberated from these carbonates would have had the relatively low values of $^{87}Sr/^{86}Sr$ characteristic of Cretaceous seawater. This works in the wrong direction. A similar effect would be expected if the bolide impacted a thick carbonate platform, which has been suggested[2] as a possible explanation for the inferred CO_2 pulse at the KT boundary. A thick carbonate platform would necessarily have had an isotopic composition reflecting some average composition of seawater, again working against a ^{87}Sr spike. Our preferred explanation is simply increased continental erosion following ecological trauma, coupled with the enhanced levels of CO_2 already alluded to.

It is our opinion that even the upper limit – 1×10^{17} moles NO – calculated by Prinn and Fegley[3] is far too high. This corresponds to raising 30% of the atmosphere to greater than 1500°K and subsequently cooling it in less than 10^4 sec. Their high estimate is founded on (1) their choice of an unreasonably massive comet as a possible impactor, and (2) their extrapolating to large impacts the observed proportionality of NO production to event energy from much smaller events.

Prinn and Fegley consider a 10^{19} g comet impacting at 65 km/sec as an upper limit. That it most certainly is. According to the conventional energy-scaled cratering relation, such a comet would have left a $\sim$ 350 km diameter basin on the moon[6]. No comparable lunar basin has formed in the past 3.8 BY, making it seem unlikely that an object that large hit Earth so recently. Also, the effects of such a huge impact would probably have been far more catastrophic than those seen at the KT boundary.

Extant developments[3-5] of impact shock chemistry treat impacts as big lightning discharges or grossly bloated hydrogen bombs. The production of interesting trace species is calculated according to a yield per erg, which for NO in the modern atmosphere is of order 10^{10} molecules/erg, or somewhat less. One then counts the ergs and multiplies.

The salient features that unify these treatments are (1) that the mass associated with the explosion itself is small, so that the explosion may be pictured as a shock expanding through an ambient medium, and essentially all the energy of the explosion is spent on shock heating atmospheric gas; (2) that subsequent cooling is very rapid, so that the freeze-out temperature is high enough to preserve large amounts of the desired high temperature products; and (3) that the events in question are not large compared with an atmospheric scale height.

For smaller impactors that are decelerated in the atmosphere, including Tunguska, these conditions are roughly satisfied and a high yield per erg is expected[7]. For large impactors that are decelerated by the crust or ocean these conditions are not satisfied and the traditional approach is unjustified. These objects form craters. Interaction with the atmosphere is mainly through ejecta. The two classes of ejecta relevant here are the rock (and probably water) vapor plume, and high speed ejecta that are widely, ballistically distributed.

Very little of the plume's energy goes into shocking the atmosphere. Only the volume of atmosphere displaced by rock vapor can get shocked. This has no direct connection with the energy of the main event. Most of the plume's energy is spent on the expansion of the plume itself. Moreover, the cooling time associated with a massive plume is relatively long, resulting in a low freeze-out temperature and relatively low yields in those gases that are shocked.

Far-flung, high-speed ejecta lofted into ballistic trajectories will on re-entry produce atmospheric shocks resembling those of a myriad of small impactors. Ejection velocities of two or three km/sec are required to give shock temperatures of order 2000°K. These secondary shocks can be relatively efficient producers of NO, provided the re-entering material is widely dispersed. When a given cylinder of atmosphere is multiply shocked only the last one matters. Also, the atmosphere can simply be overwhelmed by ejecta. Too much ejecta leaves the heated atmosphere with no place to expand. The very short cooling times associated with expansion of isolated shocked cylinders are then replaced by the very long cooling times associated with radiative cooling. Ejecta would necessarily evaporate, with unignorable chemical consequences.

Rock vapor (especially iron vapor) produced by the impact is likely to have been more reduced than the atmosphere. The mass of rock vapor produced by a large impact could easily have exceeded the mass of the atmosphere. A transient reducing atmosphere formed from the reaction of rock vapors with entrained atmospheric gases is a distinct possibility. Such an atmosphere may have been conducive to the subsequent origin of life.

We also compare the implications of our model for very large impacts with 3.5 billion year old spherule beds reported by Lowe and Byerly[8] and assigned by them an impact origin.

References

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