**PLANET EARTH SET TO BROIL: THERMAL RADIATION FROM CHICXULUB EJECTA REENTRY.**

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**Introduction:** The discovery of soot within the Chicxulub ejecta sequence [1] and the observed survival patterns of terrestrial organisms across the K/T boundary [2] led to the hypotheses that thermal radiation from the atmospheric reentry of hypervelocity impact ejecta was sufficient to ignite global wildfires [3] and cause biological catastrophe [2]. Calculations of the expected thermal radiation at the ground based on the energy deposited into the upper atmosphere by falling ejecta support this claim [3, 4, 5, 6]. We present modeling work which includes a more accurate treatment of thermal radiation transfer than previously considered. We model the atmospheric reentry and deposition of distal Chicxulub ejecta through the atmosphere and calculate the transmission of thermal radiation, both throughout the atmosphere and through time.

**Numerical Modeling:** Using a two-dimensional, two-phase fluid flow code, KFIX-LPL, we model the atmospheric reentry of Chicxulub ejecta spherules and calculate the fluxes of thermal radiation throughout the height of the atmosphere. KFIX-LPL is a version of KFIX [7], which has been modified to accommodate the complex interactions between Chicxulub ejecta and the atmosphere during atmospheric reentry at hypervelocities and subsequent sedimentation through the atmosphere onto the Earth’s surface. Because most of the high speed deceleration of spherules occurs in the upper atmosphere where the concentration of air molecules is small, we have incorporated drag coefficient and heat transfer functions [8] into KFIX-LPL which are accurate within the required ranges of velocities and flow regimes from free molecular to Stokes. In addition, we have implemented a thermal radiative transfer model into KFIX-LPL, which uses a diffusion approximation to compute the radiation energy density as a function of optical opacity. This allows us to examine the effects that greenhouse gases and the spherules themselves have on the transfer of thermal radiation to the ground.

The initial mesh approximates a 150-km-high slice of the Earth’s atmosphere into the top of which 250-µm spherules are injected. The spherules are modeled as a simple incompressible fluid with the properties of basaltic glass and enter our model atmosphere at 8 km/s and at 45° with a flux based on previous calculations of atmospheric reentry of Chicxulub ejecta [3] and the spherule mass density observed on the ground of 0.5 g/cm\(^2\) [8]. In our nominal Chicxulub scenario, the spherules reenter the atmosphere for an hour with maximum inflow at 10 minutes.

The spherules fall through the thin upper atmosphere, compressing the air as they decelerate. At 70 km in altitude, the spherules accumulate in a band of particles which becomes denser and thicker with time. Despite having lost their initial high velocities, the spherules continue to settle downwards at their fall velocities.

**Thermal Radiation Calculation:** The deceleration of spherules from hypervelocities implies the conversion of a large quantity of kinetic energy. Some of this energy heats the spherules (~1300-1600 K) and some of this energy heats the upper atmosphere (>3000 K), but the spherules are kept relatively cool due to efficient loss of heat via thermal radiation. Our models calculate the flux of thermal radiation throughout the model mesh assuming the lower boundary (ground) is absorptive but fixed in temperature (273 K) and the upper boundary is 100% transmission, meaning that any radiation reaching the top of the mesh will escape “to space”. Our models predict a pulse of thermal radiation at the ground peaking at ~6 kW/m\(^2\). However, the thermal radiation flux at the ground rapidly decreases, sustaining fluxes >5 kW/m\(^2\) for only a few minutes and fluxes above the maximum solar irradiance (1.4 kW/m\(^2\)) for 25 minutes.

![Figure 1. Thermal radiation flux (a) at the ground and (b) to space as a function of time. Negative values denote upwards fluxes.](image-url)
Discussion: Previous calculations [3, 4, 5], which did not consider spherule opacity, yielded >10 kW/m² sustained over >20 minutes and such an extended pulse of high fluxes is thought to be required for wildfire ignition [2, 6]. However, our model suggests a half-hour long pulse of abnormal thermal radiation at the ground peaking at only ~6 kW/m². Our model shows that, although a pulse of thermal radiation exceeding the solar norm is maintained for over an hour in the upper atmosphere where there are few spherules, the settling cloud of ejecta has sufficient opacity to limit transmission of thermal radiation to the ground. Large fluxes are not sustained in our models due to the increasingly opaque cloud of settling spherules, which increasingly blocks the transmission of thermal radiation from the decelerating spherules above. Hence, the spherules themselves limit the magnitude and duration of thermal radiation at the ground. Increasing thermal radiation production (i.e. injecting more spherules/injecting them faster) only enhances the strength of self-shielding. Absorption by the air further reduces the thermal radiation reaching the ground by ~50%.

Self-shielding by spherules may have prevented the ignition of global wildfires and limited other environmental effects following Chicxulub. 7 kW/m² is analogous to an oven set on “broil” so it is reasonable to expect severe thermal damage to the biosphere even if this radiation intensity is only sustained for a few minutes. However, such a thermal pulse is below the lower limits of woody biomass ignition and keeping the impact wildfire hypothesis will require a mechanism to override the self-shielding effect. A non-uniform distribution of spherule reentry may produce gaps in the opaque spherule layer through which the downward thermal radiation may be concentrated. Additionally, an unknown quantity of submicron dust particles accompanying the spherules are thought to have been injected into the upper atmosphere from the expanding impact plume. A hot opaque cap of dust in the upper atmosphere would act to reflect some of the space-bound thermal radiation downwards. We model the upper limit of this effect by employing a reflective upper boundary in our models and the resulting thermal pulse at the surface is >10 kW/m² for >20 minutes.

Figure 2. (a) Thermal radiation flux and (b) optical mean free path as a function of altitude at 10 minutes (peak spherule reentry). Note truncation of thermal radiation at altitudes corresponding to the opaque cloud of settling spherules. Opacity in the lower atmosphere is due to greenhouse gas content. Negative values denote upwards fluxes.

Figure 3. Thermal radiation flux at the ground if the upper boundary is 100% reflective (red), 50% reflective (blue), or 0% reflective (black, same as Fig. 1). Reflective upper boundary yields an upper limit for the banking ability of an opaque cap of submicron dust.