LARGE AERIAL BURSTS; AN IMPORTANT CLASS OF TERRESTRIAL ACCRETIONARY EVENTS.

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The remarkable Tunguska event occurred on the morning of 30 Jun 1908. A large meteoroid was totally disrupted at an altitude of ca. 8 km, the resulting explosion (here designated an aerial burst) having an energy of the order of 15 MT (TNT equivalent) [Vasilyev, 1998]. The blast wave leveled trees over an area of about 2000 km^2. The first field investigation two decades later showed extensive evidence of charring of the forest debris; the maximum thermal pulse at ground zero is estimated to be 238 J cm^{-2} [Korobeinikov et al., 1983], sufficient to heat 0.16 g of dry continental crust to 1500 K and melt it.

Although Tunguska is the largest aerial burst recorded in human history, there are good reasons to believe that it is one of a continuum of such accretionary events that extends from events $<10^3$ times smaller to events $>10^6$ times larger. The smallest documented members of the set are the type-III fireballs recorded by the cameras of fireball networks [Ceplecha et al., 1998]. A number of events of intermediate size are recorded by military satellites [Tagliaferri et al., 1995].

It would appear that a combination of two circumstances are required to generate aerial bursts appreciably larger in magnitude than Tunguska: (1) the meteoroid must be weak enough to disrupt during atmospheric passage, and (2) the atmospheric entry angle must be relatively oblique. If we assume a density of 2 g cm^{-3}, the radius of the Tunguska meteoroid is estimated to be about 40 m. Its entry angle seems to have been in the range 20-45° relative to the horizontal [Bronshten, 1999]. Modeling by Hills and Goda [1999] indicates that a friable meteorite (strength of $1 \bullet 10^8$ dynes cm^{-2}) must have a radium 100 m to deposit half its energy at the Earth's solid surface at an entry angle of 90° and a geocentric velocity of 18 km s^{-1}. These authors estimate that a 500 m projectile will lose half its energy at 10 km if its entry angle is 20°.

For Tunguska-size object the blast effects are more dramatic than the thermal effects, but thermal effects dominate as the size of the event increases. The reason for this is that, as the size of the event increases, the central region finds itself surrounded by atmosphere that is also hot, and loses its ability to cool itself by radiation in directions other than vertical. Because there is so little mass above the hot gas, expansion results in negligible cooling.

Below this central region of the burst we can expect vegetation to be fully incinerated. In moist, vegetated areas or regions covered by water, much of the heat energy is expended on the latent heat of vaporization of H_2O and carbonaceous compounds, and the temperatures of unvaporized solid (or liquid) materials remain relatively low. In contrast, if the surface below the burst is desert-like, the radiation is capable of melting a several mm of the sand or rock.

When large craters such as Chicxulub form, the ejecta is thrown above the atmosphere and scattered around all regions of the globe. The entry of this ejecta into the atmosphere causes large amounts of heating, creating conditions much like those resulting from an aerial burst. Thus, the incineration of vegetation is common to these two phenomena. The chief environmental difference is one of scale, the Chicxulub event being global, the mega-Tunguska events regional.

Materials which we interpret to be the products of giant aerial bursts are the layered (or

Muong-Nong-type) tektites found over a region having an area of ≈8•10^5 km^2 in Southeast Asia and the Libyan Desert Glass (LDG) found over a region having an area of ≈7•10^3 km^2 in Western Egypt. These are glassy materials which were formed by the melting of surficial materials on the local continental crust. Compositions of layered tektites are about the same as the local continental crust; a small enrichment in SiO_2 may be a selection effect resulting from an increased resistance to devitrification or weathering. The LDG is ≈98% SiO_2, similar in composition to the adjacent Great Sand Sea. The layering common to both these materials is inferred to have resulted from down-slope flow of a melt sheet. This flow implies that temperatures remained high (>2400 K) for several minutes.

The most common origin ascribed to these materials in the past is ejection from craters. However, there is no evidence that large amounts of fully molten materials are ever ejected from terrestrial craters, and any such ejecta would be expected to quench when it returns to the surface. Cratering events do not offer a mechanism to keep thin layers of melt hot enough to flow tens of cm. In addition, melt production is most efficient a the bottoms of craters, whereas all layered tektites have high 10Be contents requiring that much or most of the target have been a surficial soil.

The very low density (1.3 g cm^{-3}) of the asteroid Mathilde [Veverka et al., 1999] suggests that it is a flying rubble pile. It is plausible that a sizable fraction of asteroids and comets are primordial materials that were never compacted, and have essentially no strength. If this is correct, then many of the asteroids striking the Earth may be these strengthless objects. Another fact in support of this hypothesis is the high fraction of low-strength fireballs observed by the photographic networks; weak meteoroids are recognized because they break up higher in the atmosphere. According to the summary of Ceplecha et al. [1998], only 32% of photographed meteoroids have the strength of irons or anhydrous chondrites. Another 33% are friable, having strengths similar to CM chondrites, and the remaining 35% are designated "cometary" because they break up very high at extremely low dynamic pressures.

Given the strength of the interplanetary source it is plausible that aerial bursts should comprise an important fraction of the accretionary events occurring on the Earth. A goal of our future research is to better calibrate the relationship between entry angle and the fraction of the kinetic energy deposited in the atmosphere, and thus to estimate the magnitude-frequency of such events. Our preliminary modeling indicates that highly oblique impacts of relatively strong meteoroids can deposit most of their kinetic energy in the atmosphere even though much of the projectile penetrates to the surface.

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