METEORITE IMPACT AND THE EXTINCTION OF SOLAR RADIATION; John D. O'Keefe and Thomas J. Ahrens, Seismological Laboratory 252-21, California Institute of Technology, Pasadena, California 91125.

The mechanisms for the extinction of biota by impact events depend critically upon the distribution of fine particles ($<1\ \mu$m) ejected into the atmosphere. Toon et al. (1982), Gerstl and Zardecki (1982), Turco et al. (1983), and Malone et al. (1986) have shown that only the fine particles have atmospheric residence times that are sufficient to cause significant climatological and thus biological effects.

We have extended our previous (O'Keefe and Ahrens, 1985, 1987). model of fragment size-velocity distribution to account for the change in the distribution function for the fine particles (Gault et al., 1963; Asada, 1985). In this approach we have used: 1) numerical simulations of impact ejecta mass vs. velocity, 2) ejecta blanket size distributions, 3) observations and theories of maximum ejecta fragment size vs. velocity, 4) an assumption on the functional form of the distribution function of the fragments ejected at a given velocity, 5) laboratory and field data on the transition point for the fine fragment distribution function, and 6) theoretical considerations on size of the smallest fragments.

The fraction of mass $dM(l)$ with fragment sizes less than l ejected at a given position, R, is given by

$$\frac{dM(l,R)}{M_T} \equiv \frac{\rho\, dV}{M_T}\ \frac{\int_0^l \frac{\partial N_c}{\partial l}\, l^3\, dl}{\int_0^\lambda \frac{\partial N_c}{\partial l}\, l^3\, dl} \tag{1}$$

where λ is the largest fragment size, ejected at a given position, R, M_T is the total ejecta mass, N_c is the fragment cumulative number density, ρ, is the solid density, and dV is the volume increment. We have chosen to use the modified Mott distribution. This has been successful in describing the distributions of fragments in explosion cratering (Slotky et al., 1985). This distribution is

$$\frac{\partial N_c}{\partial l} = \frac{N_T}{\lambda\left(\frac{l_o}{\lambda}\right)^u \Gamma\,(u+1)} \left(\frac{l}{\lambda}\right)^u \exp\left(-\frac{l}{\lambda}\right) \quad l_o > 0 \tag{2}$$

Here N_T is the total number of fragments and Γ is the complete gamma function. When $u = 0$, the above is the standard Mott distribution and when $u \neq 0$, the distribution is more polydispersed and implies that more grinding and crushing occurred than in a single fragmentation event. Equations (1) and (2) can be integrated to give

$$\frac{dM\,(l,R)}{M_T} = \underbrace{\frac{\rho dV(R)}{M_T}}_{\substack{\text{fraction of}\\ \text{mass ejected}\\ \text{at R}}}\ \underbrace{\frac{\gamma\left(\beta, \frac{l}{\lambda\,(R)}\right)}{\gamma\,(\beta, \infty)}}_{\substack{\text{fraction of}\\ \text{fragments less}\\ \text{than } l}} \tag{3}$$

where γ is the incomplete gamma function and β is the parameter which describes the distribution of ejecta mass traveling at a given velocity. For $\beta > 3$ the ejecta traveling at a given velocity is more mono-dispersed, whereas when the value of β goes from 3 to 0, the particle sizes traveling at different velocities have a broad range of sizes limited by the maximum size, λ. Using the theory of Grady and Kipp (1980) and strain-rate fields from numerical simulations (O'Keefe and Ahrens, 1977) it can be shown that the parameter describing the variation of the largest particle traveling at a given velocity, δ, has a value ~ 3 (O'Keefe and Ahrens, 1985). This value of δ was shown to be consistent with chemical and explosion data (Schoutens, 1979), the planetary observations (Vickery, 1986) and the spallation theory of Melosh (1984). The cumulative mass of fragments whose sizes are less than l that are ejected at velocities greater than V, is given by

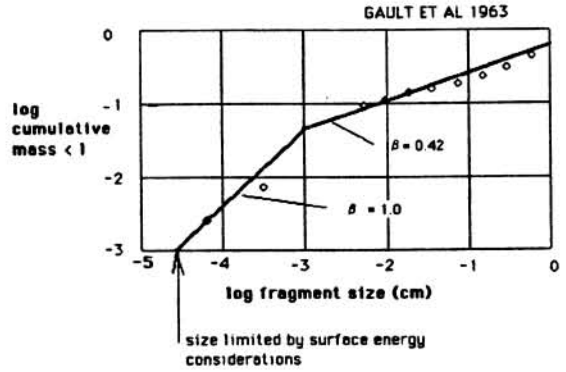
$$\frac{dM\,(l, V)}{M_T} = \frac{\gamma\left(\beta, \frac{l}{\lambda L}\left(\frac{V}{V_{min}}\right)^{\frac{\delta}{3}}\right)}{\gamma\left(\beta, \infty\right)}\ \frac{\epsilon\left(\frac{V}{V_{min}}\right)^{-(\xi-1)}}{\left(1 - \left(\frac{V_{min}}{V_{max}}\right)^{\xi}\right)}\ \frac{dV}{V_{min}} \tag{4}$$

where V_{min} and V_{max} are the minimum and maximum velocities of ejection and the parameter, ξ, is found to have a value of approximately 1.4 (O'Keefe and Ahrens, 1985).

The parameter, β, (Eq. 4) has been adjusted to give a best fit to laboratory data in both the coarse and fine particle regimes. Shown in figure 1 is the data of Gault et al. (1963) and those fits. The coarse distribution of fragments is polydispersed whereas the fine fragments are more monodispersed. The reason the fine fragments are more monodispersed may be the depletion of flaws at the micron scale. The smallest fragment size is constrained to be $>0.1\ \mu$m taking into account the energy required to create new surface area is approaching the energy of melting. Using those parameters, we have calculated the mass of fine particles that are ejected into the atmosphere as a function of ejected mass (see figure 2). Gerstl and Zardecki (1982) calculated that on the order of 10^{16} g of fine dust are required to shield the earth from the sun. From our calculations this implies that the total mass ejected was on the order of 10^{20} g. This latter value is in the range of values estimated from considerations of the amount of mass in the K-T boundary layer (Alvarez et al., 1980). These fine particles can be distributed world-wide because as the impactor penetrates the atmosphere it creates an upward motion of the atmosphere that would entrain and distribute them globally (O'Keefe and Ahrens, 1982).

References: **(1)** Asada, N. (1985), Fine fragments in high-velocity impact experiments, *J. Geophys. Res., 90,* 12,445-12,454. **(2)** Gault, D. E., E. M. Shoemaker, and H. J. Moore (1963), Spray ejected from the lunar surface by meteoroid impact , *NASA Publication TND-1767,* p. 39. **(3)** Gerstl, S. A. W. and Z. Zardecki (1982), Reduction of photosynthetically active radiation under extreme stratospheric aerosol loading, *Proc. Conf. Large Body Impact, Sp. Paper 190, Geol. Soc. Am.,* 201-210. **(4)** Grady, D. E. and E. Kipp (1980), Continuum modeling of explosive fracture in oil shale, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 17,* 147-157. **(5)** Malone, R. C., L. H. Auer, G. A. Glatzmaier, M. C. Wood, and O. B. Toon (1986), Nuclear winter: Three-dimensional simulations including interactive transport, scavenging, and solar heating of smoke, *J. Geophys. Res., 91,* 1039-1053. **(6)** Melosh, H. J. (1984), Impact ejection spallation, and the origin of the meteorites, *Icarus, 59,* 234-260. **(7)** O'Keefe, J. D. and Ahrens, T. J. (1977), Impact induced energy partitioning, melting, and vaporization on terrestrial planets, *Proc. Lunar Sci. Conf., 8th,* 3357-3374. **(8)** O'Keefe, J. D. and T. J. Ahrens (1982), The interaction of the Cretaceous-Tertiary extinction bolide with the atmosphere, ocean, and solid earth, *Proc. Conf. on Large Body Impactsd and Terrestrial Evolution, Sp. Paper #190* , Geol. Soc. Am., 103-120. **(9)** O'Keefe, J. D. and T. J. Ahrens (1985), Impact and explosion crater ejecta, fragment size, and velocity, *Icarus, 62,* 328-338. **(10)** O'Keefe, J. D. and T. J. Ahrens (1987), The size distributions of fragments ejected at a given velocity from impact craters, *Int. J. Impact Engineering, Proc. Hypervelocity Impact Symp.,* San Antonio, TX, Oct. 21-24. **(11)** Schoutens, J. E. (1979), Empirical analysis of nuclear and high-explosive cratering and ejecta, *Nuclear Geoplosics Sourcebook, IV,* Part II, Rep. DNA6501H-4-2, Defense Nuclear Agency, Washington, D.C. **(12)** Slotky, D., Z. Jaeger, and R. Englman (1987), Distribution of fragments in a series of explosions in the Rotem oil shale fields - theory and experiment, *Proc. Symp. on Fragmentation, Soc. of Explosives Engineers,* p. 130. **(13)** Toon, O. B., J. B. Pollack, R. P. Turco, C P. McKay, and M. Liu (1981), Large body impacts: Evolution of the dust cloud and it's effects on the atmosphere, *(Conf. on Large Body Impacts, Snowbird, Utah, Oct. 19-22, 1981),* Geol. Soc. Am. Spec. Pap. 190. **(14)** Vickery, A. M. (1986), Size-velocity distribution of large ejecta fragments, *Icarus, 67,* 224-236.

COMPARISON OF THEORY WITH LABORATORY IMPACT DATA



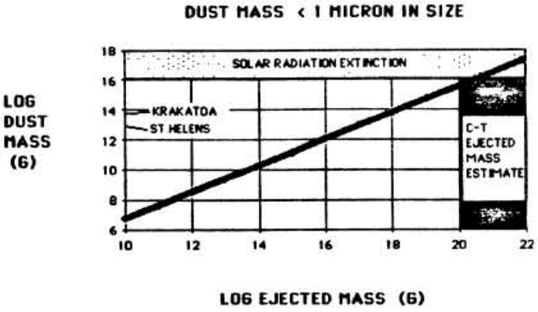


Fig. 1. The cumulative amount of mass of fragments having diameters less than 1 micron as a function of fragment size. The data is from Gault et al. (1963). Note that the distribution has a different slope for small fragments.

Fig. 2. Amount of mass of fragments whose diameters are less than 1 micron that is ejected into the atmosphere as a function of the total amount of mass ejected.