LOSS OF THE EARTH'S ATMOSPHERE FROM GIANT IMPACTS; Thomas J. Ahrens and John D. O'Keefe, Seismological Laboratory 252-21, California Institute of Technology, Pasadena, CA 91125.

Cameron (1983) pointed out that impact cratering can cause significant loss of an early, dense, planetary atmosphere such as has been described by Holland (1984) and others. Because of the strong mechanical impedance mismatch between the air and silicate, the calculation of the impact interaction of a projectile with an atmosphere, especially description of the ejecta interaction, is difficult (Walker, 1986). Hassig et al. (1986) found that for an exponential atmosphere only 0.1% of the energy is transferred to the atmosphere upon initial passage of a 10 km diameter, 20 km/sec bolide. Earlier (O'Keefe and Ahrens, 1982a,b) studied the interaction of a 5 km/sec, 10 km diameter silicate impactor interacting with a silicate halfspace covered with a 10 km thick layer of air. The total fraction of energy initially partitioned into the atmospheric layer is $<1\%$ of the bolide energy. However after impact most of the kinetic and internal energy of the ejecta is also later transferred to the atmosphere via drag forces, radiation and conduction processes. Thus O'Keefe and Ahrens (1982a) estimated some 0.39 fraction of the total energy of a very large bolide ($\sim 10^{28}$ ergs) would be transferred to the atmosphere. This efficiency of transfer depends critically upon the distribution of fragments and condensed vapor ejected from the crater and its interaction with the atmosphere. Depending on density, smaller ($\sim 10^2$ m diameter) objects transfer virtually all their energy into the atmosphere. Thus when impactors with energies $>10^{28}$ ergs impact the earth virtually all their interactions with the atmosphere occur very near the surface.

Using the approximation that the energy of the impactor is effectively delivered to the atmosphere at the surface (expected to be closely valid for projectile energies $>10^{28}$ erg) we have examined the shock-induced flow from such impacts on the earth for an exponential atmosphere. This interesting problem has been studied by Zel'dovich and Raizer (1967) and is often called the Zel'dovich flow. In an exponential atmosphere the downward propagating shock (from a finite height explosion) slows down and the upward propagating shock accelerates in both shock velocity and particle velocity behind the shock front. The general idea of the Zel'dovich flow is demonstrated in Fig. 1 in which the shock front is shown at various non-dimensional times, T. T is related to real time, t, by

$$T = t[E_o/(4\pi\Delta^5 \rho_c J_o)]^{1/2} \equiv At$$

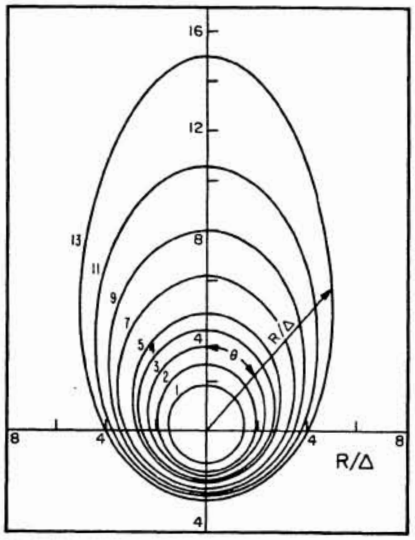
where E_o is the energy of the explosion, Δ, is the atmospheric scale height (7 km for the earth), ρ_c is the density at the height of the explosion (taken here to be 10^{-3}g/cm^3) and $J_o = 0.4233$ is a constant which is a function of the polytropic exponent, γ, of the atmosphere (γ is taken to be 1.4). Thus one can see that as a shock propagates upward it accelerates. For altitudes which are a factor of 10 greater than the atmospheric scale height, we assume that when the calculated outward particle velocity is greater than the earth's escape velocity (11 km/sec) the gas in these regions escapes the earth. Within the framework of the present theory of atmospheric escape for an atmosphere lying above a halfspace (no earth curvature) the maximum mass of gas which can escape from a single explosion or impact will be the mass of gas above a plane tangent to the spherical earth. For the above atmospheric parameters, this mass of gas is 2.6×10^{18} g and compares to a mass of 1.6×10^{16} g which is the largest mass which we calculate can escape from a single impact (Fig. 2). Thus we conclude that within the framework of the Zel'dovich flow problem, only some 5×10^{-6} of the total atmosphere of the earth can be lost by a single impact. According to Table 1, the minimum coupled impact energy for this maximal atmospheric loss event is in the range of 0.5×10^{30} to 1×10^{30} ergs. This corresponds to a 2 g/cm^3 density, 3-6 km diameter, projectile infalling at 11 km/sec into the present atmosphere. This maximal efficiency of atmospheric loss projectile is only a factor of ~ 10 lower in energy than that inferred by Alvarez et al. (1980), O'Keefe and Ahrens (1982b) for the Cretaceous-Tertiary extinction bolide.

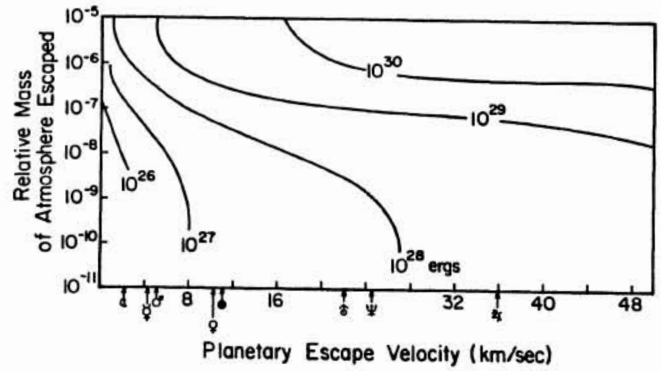
Finally, we note that actually a very narrow energy regime range exists between the energy for maximal efficiency loss (10^{30} ergs) versus that for impacts (or explosion) for which the result is total atmospheric retention which occurs for an escape velocity of 11 km/sec. Total atmospheric retention occurs for impacts with coupled energies less than 10^{27} ergs.

REFERENCES: **(1)**. Cameron, A. G. W. (1983), Origin of the atmospheres of the terrestrial planets, *Icarus, 56,* 195-201. **(2)**. Hassig, P. J., M. Rosenblatt, and D. J. Roddy (1985), Analytical simulation of a 10-km-diameter asteroid impact onto a terrestrial ocean; Part 2- Atmospheric response; *Lunar and Planet. Sci. XVII,* 321-327. **(3)**. Holland, H. D. (1984), The chemical evolution of the atmosphere and oceans, Princeton Univ. Press, 582 pp. **(4)**. O'Keefe, J. D. and T. J. Ahrens (1982a), The interaction of the Cretaceous-Tertiary extinction bolide with the atmosphere, ocean, and solid earth, *Proc. Conf. on Large Body Impacts and Terrestrial Evolution, Sp. Paper #190 Geol. Soc. Am.,* 103-120. **(5)**. O'Keefe, J. D. and T. J. Ahrens (1982b),

ATMOSPHERIC CRATERING
Ahrens, T. J. and O'Keefe, J. D.

Impact mechanics of the Cretaceous-Tertiary extinction bolide, *Nature, 298,* 123-127. (6).
Walker, J. C. G. (1986), Impact erosion of planetary atmospheres, *Icarus, 68,* 87-98. (7).
Zel'dovich, Ya. B. and Yu. P. Raizer (1967), *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Vol. II,* Academic Press, NY.





TJA86067MFD

Fig. 1. Shock envelopes for various values of the non-dimensional time scale T(γ=1.4).

Fig. 2. Relative mass of a hemisphere of atmosphere, which will escape for an exponential atmosphere with $\gamma = 1.4$, $\rho_a = 10^{-}3 g/cm^3$, and $\Delta = 7$ km, versus, planetary escape velocity. For comparison escape velocity for moon, Mercury, Mars, Venus, Earth, Uranus, Neptune, and Saturn is indicated.

Table 1. Mass Fraction of Atmospheric Hemisphere Lofted to Escape vs. Planetary Escape Velocity

Energy (ergs)	Velocity (km/sec) 1	2	3	4	5	6	7	8	9	10	11	30	50
1.0×10^{26}	4.4-08*	7.0-09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5×10^{27}	4.4-07	1.1-07	2.2-08	8.8-09	3.5-09	5.6-11	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0×10^{27}	5.6-07	1.1-07	4.4-08	4.4-08	1.8-08	8.8-09	3.5-09	2.2-10	0.0	0.0	0.0	0.0	0.0
0.5×10^{28}	8.8-06	5.6-07	4.4-07	1.1-07	1.1-07	1.1-07	4.4-08	4.4-08	4.4-08	1.8-08	1.8-08	0.0	0.0
1.0×10^{28}	8.8-08	5.6-07	5.6-07	4.4-07	4.4-07	1.1-07	1.1-07	1.1-07	1.1-07	4.4-08	4.4-06	0.0	0.0
0.5×10^{29}	8.8-06	8.8-06	8.8-06	5.6-07	5.6-07	5.6-07	5.6-07	5.6-07	4.4-07	4.4-07	4.4-07	2.2-08	3.5-09
1.0×10^{29}	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	1.1-06	5.6-07	5.6-07	5.6-07	5.6-07	5.6-07	4.4-08	4.8-08
0.5×10^{30}	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	1.8-06	4.4-07	1.1-07
1.0×10^{30}	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	8.8-06	5.6-07	4.4-07

*4.4×10^{-8}