ATMOSPHERIC EROSION BY IMPACTS: AN ANALYTIC INVESTIGATION

A. M. Vickery and H.J. Melosh, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721

Until recently, models for the origin and evolution of the atmospheres of terrestrial planets ignored the effects of accretionary impacts. In the 1970's, however, it was suggested that heating and/or vaporization of accreting carbonaceous-chondrite-type planetesimals could result in the release of their volatile components (1,2). Modeling of this process (e.g., 3,4) strongly suggests that substantial atmospheres/hydrospheres could develop this way. During most of the accretionary process, impact velocities generally differed little from the escape velocity of the growing proto-planet because most of the collisions were between bodies in nearly matching orbits. Toward the end of accretion, however, collisions were rarer but much more energetic, involving large planetesimals and higher impact velocities (5). It has been postulated that such impacts result in a net loss of atmosphere from a planet, and that the cumulative effect impacts during the period of heavy bombardment might have dramatically depleted the original atmospheres (6,7).

The transfer of momentum from an impactor to an atmosphere can occur in a number of ways. First there is the direct transfer of momentum as the impactor penetrates the atmosphere, compressing and accelerating the gas in front of it. O'Keefe and Ahrens (8) showed that the impactor delivers only a small fraction of its kinetic energy directly to the atmosphere, and Walker (9) showed that this energy is distributed in such a way that no significant amount of atmosphere escapes from a planet with an escape velocity $\geq$ 10 km/s. Second, solid ejecta thrown out of the growing crater can similarly transfer momentum to the atmosphere, but again this has been shown to result in negligible atmospheric loss (10). Third, for a sufficiently energetic impact, a great deal of very hot, dense vaporized impactor $\pm$ target material will be produced that expands upward and outward at high velocities, driving the overlying atmosphere ahead of it.

The initial pressures in the impact-generated gas cloud will be so much higher than atmospheric pressure that one can, as a first approximation, consider the gas to be expanding in a vacuum. We used the analytic solutions of (11) to calculate the momentum of the impact gas, for which we needed to specify the mass and initial pressure and density of the gas. The pressure as a function of impact velocity for velocities of 10 to 50 km/s was estimated using impedance-matching (12), and the density was then estimated from the Rankine-Hugoniot relations. The mass of gas was arbitrarily chosen to range from 10^{10} kg to 10^{20} kg.

The maximum amount of atmosphere that can potentially be blown off in a single impact is that lying above a plane tangent to the planet's surface at the point of impact. We derived the following equation to calculate the mass of atmosphere as a function of zenith angle lying above the tangent plane :

$$\frac{dM}{d\theta} = 2\pi \sin\theta \int \frac{\rho(z)\left[\sqrt{z^2+2Rz+R^2\cos^2\theta} - R\cos\theta\right]^2 (R+z)\,dz}{\sqrt{z^2+2Rz+R^2\cos^2\theta}}$$

where θ is the angle from the zenith, z is altitude, ρ is density, and R is the radius of the planet. The atmospheric density profile for the earth was taken from (13), while those for Mars and Venus were calculated from temperature profiles, surface temperatures and pressures (13), the equation for hydrostatic equilibrium, and the perfect gas law. A series of calculations was also performed for a hypothetical primitve Martian atmosphere, arbitrarily chosen to be isothermal (T=300 K) and to have a surface pressure of 10^5 Pa and surface density of 1 kg/m^3. The results are shown in figures 1-4. As one would intuitively expect, the fraction of atmosphere blown off increases with both impact velocity and mass of impact-produced gas. The efficiency with which atmosphere is removed for a given impact velocity and impact gas mass increases in the order Venus, Earth, Mars, and the hypothetical primitive atmosphere of Mars is more efficiently removed than that of present day earth (which it resembles in surface pressure and density) because of Mars' lesser gravity.

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The mass of impact gas is used as a parameter in these calculations rather than the mass of the impactor. This makes it impossible to cast these results in terms of impact energy or momentum, but was necessary because the use of the Zel'dovich-Razier equations (11) is only valid for the initial gas pressures >> ambient atmospheric pressure, and there is no reliable way to estimate the mass of such gas as a function of impactor mass and impact velocity. Another complication is that oblique impacts apparently produce much more vapor than normal impacts with the same impactor mass and impact velocity (14).

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