PRESSURE DEPENDENCE OF ATMOSPHERIC LOSS BY IMPACT-INDUCED VAPOR EXPANSION.

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Introduction: The large number of impacts would have many consequences on the evolution of planetary atmospheres. Melosh and Vickery [1] analytically estimated the lower limit of impactor mass and velocity which could blow off all the atmosphere above the tangent plane to the impact point and suggested the possibility of the substantial atmospheric loss on Mars by impacts during the heavy bombardment. In their estimate, the mass of the atmospheric loss is to be proportional to the planetary atmospheric pressure. Several groups performed numerical calculations using an analytical model or hydrodynamic codes to evaluate the effect on the atmospheric mass by impacts more quantitatively [2-4]. However, they focus mostly on the effect under the present Earth atmosphere, i.e atmospheric pressure is about 1 bar. The atmospheric pressure differs by the planets (~90 bar for Venus and ~10 mbar for Mars), and is the quantity that could change greatly through its evolution. In order to discuss the atmospheric loss by impacts through the evolution of the atmospheres, it is required to consider the effect by the atmospheric pressure on the mass of the atmospheric loss by impacts.

We carried out several runs with various atmospheric pressure by using a 2-D cylindrical hydrocode and investigated the dependence of the mass of the atmospheric loss on the atmospheric pressure.

Numerical Calculations: We considered a vapor expansion in a planetary atmosphere, which is gravitationally bound to the planet. The atmosphere is assumed to be isothermal. The vapor cloud, which is generated by the impact, is considered to be homogeneous and at rest initially within a hemisphere centered at the impact point. We approximated both the atmosphere and vapor cloud as an ideal gas.

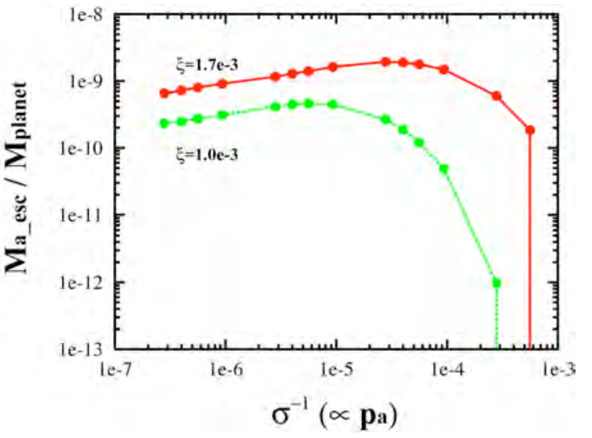

Fig. 1. Parameter dependence of atmospheric escape mass M_{a_esc} on atmospheric pressure p_a at the planetary surface: $\xi = 1.7\text{e-}3$ (red) and $\xi = 1.0\text{e-}3$ (green). Both axes are written with non-dimensional quantities. Other parameters are set like this: $\lambda_a = 700$ and $\varepsilon = 1$.

To calculate the motion of the atmosphere with the vapor expansion and the mass of atmospheric loss, we developed a 2-D cylindrical hydrocode. This code is based on the algorithm CIP (Cubic Interpolated Propagation) [5]. The entire computational region is resolved into 180×180 grids. The spatial interval is 0.1 r_v for the initial vapor cloud, where r_v is the initial vapor radius. The interval in the other region increases by a geometric series.

We normalized hydrodynamic equations and initial conditions by using appropriate scales and then derived four dimensionless parameters as follows,

$$\xi \equiv \frac{r_v}{R},\ \lambda_a \equiv \frac{R}{H_a},\ \varepsilon \equiv \frac{e_v}{V_e^{2}/2},\ \sigma \equiv \frac{\rho_v V_e^{2}/2}{p_a},$$

where R and V_e are the planetary radius and escape velocity, respectively. p_a and H_a are the atmospheric pressure and scale height, respectively. e_v and ρ_v are the specific internal energy and density of the initial vapor cloud. All the motion of the atmosphere and vapor cloud is described by these four parameters.

Results and Discussion: We considered that the atmosphere would escape from the planet when its velocity exceeds V_e. The mass of the escaping atmosphere rapidly increases at first with the acceleration due to the vapor expansion and then level off. We defined the final value as the mass of the atmospheric loss. In Figure 1, we can see that the mass of the atmospheric loss shows the less dependence for the smaller atmospheric pressure, compared with the linear dependence by Melosh and Vickery [1]. Thus, two orders of magnitude change in the atmospheric pressure causes less than factor of three change in the amount of the atmospheric loss. With an increase of the atmospheric pressure, the mass of the atmospheric loss steeply decreases beyond a certain critical pressure and finally no atmospheric loss occurs.

We calculated the atmospheric escape region, i.e. where the atmosphere is lost, to understand the dependence on the atmospheric pressure (Fig. 2). For the larger atmospheric pressure, the escape region is

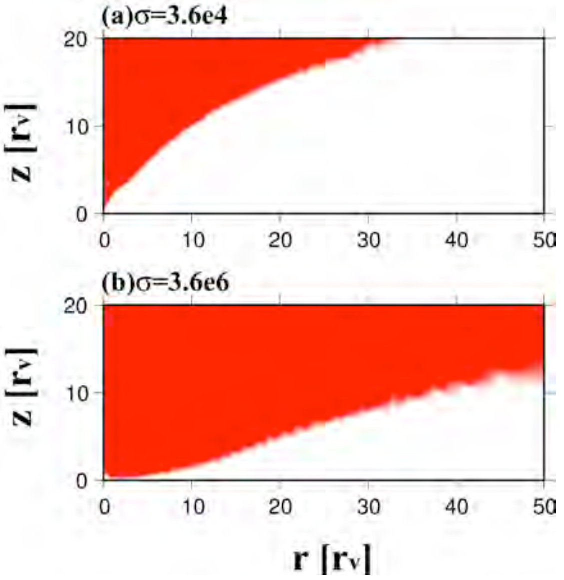

Fig. 2. Atmospheric escape region: (a) σ= 3.6e4 and (b) σ = 3.6e6. Other parameters are ξ= 1.0e-3, λ_a = 700 and ε = 1. Coordinates (r and z) are normalized by initial vapor radius. Normalized atmospheric scale height corresponds to about 1.4 in these figures

like cone-shaped (Fig. 2(a)). Note that the escape region bulges out near the planetary surface and it seems that the more atmosphere near the surface escapes in Figure 2(b). The explosive vapor expansion can sweep out the ambient atmosphere near the surface further away for the smaller atmospheric pressure. The swept atmosphere is compressed to high pressures as well as accelerated almost radially. The atmosphere near the planetary surface cannot escape radially due to high density by the gravitational stratification. However, when the atmospheric pressure is small, the compressed atmosphere changes the direction of its motion upward by its own pressure and some fraction of the atmosphere near the surface can escape. Consequently, the dependence of the atmosphere escapes on the atmospheric pressure is less than the linear dependence suggested by Melosh and Vickery [1].

The ejecta curtain may prevent the vapor cloud to expand horizontally. Based on a simple estimation we found that the expansion velocity of the vapor cloud would be faster than that of the ejecta. Thus, we estimate that the loss of ambient atmosphere is not much affected by ejecta. However, the early stage of the impact is complicated and the various phenomena, such as the energy partition between the vapor cloud and the excavation flow and the rising of the ejecta curtain, occur simultaneously. Thus, the effect of the ejecta still remains uncertain.

Shuvalov and Artemieva [4] suggest that the vertical impact causes less atmospheric loss because the generated vapor cloud moves through the wake (i.e. the hole opened in the atmosphere by the impactor penetration) to high altitude. We performed preliminary calculations with the different initial condition to examine the effect of the wake (Table 1). The runs have the same total energy of the initial vapor cloud but the different initial energy partition (K_v/U_v) or direction of its initial velocity. The results without and with wake are almost the same (case 1 and 2). In contrast, the mass of the atmospheric loss in the case 4 (with K_v/U_v equals 1 and upward velocity) is less by a factor of ten than in the other cases. This suggests that the direction of the initial motion is essential factor that affects the atmospheric loss. The results by Shuvalov and Artemieva [4] that oblique impacts would blow off more atmospheric mass than vertical impacts would be resulted by the difference in the direction of the initial velocity, not by the wake.

Table 1. The results with the different initial conditions with respect to the energy

	case 1	case 2	case 3	case 4
K_v / U_v	0	0	1	1
Wake	no	wake	no	no
Direction of the initial vapor velocity	-	-	isotropic	upward
M_{a_esc}/ M_{planet}	3.8e-11	3.7e-11	3.6e-11	5.4e-12

A used parameter set is (ξ, λ_a, ε, σ)=(1.2e-3, 700, 0.77, 7.1e5). The total energy of the initial vapor cloud are same for all cases. K_v and U_v are the kinetic and internal energy of the initial vapor cloud, respectively. M_{a_esc} and M_{planet} are the mass of the atmospheric loss and the planet, respectively.

Summary: We investigated the effect of the atmospheric pressure on the mass of the atmospheric loss by impacts. No atmospheric loss occurs for the too large atmospheric pressure, while for the smaller atmospheric pressure, the mass of atmospheric loss changes only by a factor of less than three when the atmospheric pressure changes two orders of magnitude. The results of the preliminary calculations suggest that the oblique impacts is more effective on the atmospheric loss than the vertical impacts as suggested by Shuvalov and Artimieva [4] and, however, that it would be caused by the difference of the direction of the initial motion of the vapor cloud rather than the occurrence of the wake.

References: [1] Melosh H. J. and Vickery A. M. (1989) *Nature, 338,* 487–490.[2] Vickery A. M. and Melosh H. J. (1990) *Geol. Soc. Am. Sp. Pap. 247,* 289–300. [3] Newman,W.I. et al. (1999) *Icarus,* 138, 224–240. [4] Shuvalov V. V. and Artemieva N. A. (2002) *Geol. Soc. Am. Sp. Pap.* 356, 695–703. [5] Yabe T. et al. (1991) *Computer Physics Communications, 66,233-242.*