Erosion of planetary atmosphere due to surface waves induced by giant impact. A. H. Shen[1], T. J. Ahrens[2], and S. Ni[3] (all at Seismological Laboratory, Caltech, Pasadena, CA 91125; email: [1]ahshen@caltech.edu; [2]tja@gps.caltech.edu; [3]stone@gps.caltech.edu)

Introduction: The idea of erosion of planetary atmosphere by giant impact was introduced by early works of Arrhenius et al. [1], Benlow and Meaows[2], Ringwood [3] and Cameron [4]. This idea was further expanded by other researchers to study the blow-off of atmosphere by other mechanisms due to the impactor [5-7]. Ahrens [8] described the degree of atmosphere erosion due to the surface wave induced by a giant impact on planetary surface. He also calculated the amount of erosion achievable at different surface wave velocity. Chen and Ahrens [9] further simulated the amplification of particle velocity in the atmosphere column perturbed by the planetary surface with 2 km/s velocity using a gravity-added Lagrangian hydrodynamic code, WONDY [10]. With this simple model, Chen and Ahrens demonstrated that the motion of the planetary surface is sufficient to launch the air particles to escape velocity. Ni and Ahrens [11] constructed the propagation of surface wave due to a giant impact with 10^{27} J energy on a hypothetical, homogenous planet about the same size as the Earth. Their main result is a series of the surface velocities at several stations of equal distances (10º separation) from the impact point. In this contribution, we report our effort in further modification of the WONDY code so that the surface velocities determined by Ni and Ahrens can be imported to WONDY as a time sequence of boundary conditions.

Simulation Methods: We modified WONDY, a one-dimensional, finite-difference, compressible fluid dynamics, Lagrangian code for the simulation. The code was modified from its original form in the following ways:

1. Earth gravity was added to the initialization and the equations of motion. Before impact, the atmosphere is isothermal at 300K and gravitationally stable, its density decays exponentially with altitude. A scale height of 8 km is used for the Earth's atmosphere.
2. Re-meshing criterion was changed from stress to mass.
3. The ground velocity at the atmosphere-ground boundary can be imported as a time sequence.
4. Ground velocities between two time sequence points were interpolated using a simple linear interpolation algorithm.

The geometry of the Earth-atmosphere in this study is a 6400 km radius shell with density of 2500 kg/m^3. On top of the shell is a 128 km thick atmosphere (air density at the shell-atmosphere interface is 1 kg/m^3 and pressure is 10^5 pa). The gravity is 9.8 m/s^2 at the ground-atmosphere boundary.

Data from Ni and Ahrens [11] consisted of 19 time sequences which represent the ground motions at stations separated 10º from each other in a half sphere along the great circle and the other half is symmetrical due to the normal impact geometry in their calculation. These data were imported into the WONDY code as the ground –atmosphere boundary conditions at different time as the simulation proceeded.

We scaled Ni and Ahrens' data to simulate the ground velocity profiles with impact energy varying from 5.5 x 10^{25} J to 1.4 x 10^{27} J.

Results and Discussions:

Our simulation results are summarized in Table 1 and 2.

Epicenter Distance	Impact Energy (J)			
Angle(º)	1.5E+26	3.0E+26	6.1E+26	1.4E+27
0	1.6E-03	8.4E-03	4.1E-02	1.5E-01
30	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0
90	0.0	0.0	0.0	0.0
120	0.0	0.0	0.0	0.0
150	0.0	0.0	0.0	0.0
180	0.0	4.3E-06	1.7E-05	1.0E-04

Table 1. Fraction of atmosphere mass reaching the escape velocity of the Earth (11.2 km/s) at selected directions. The angles are the angles from the impact point along a great circle.

Epicenter Distance	Impact Energy (J)			
Angle(º)	1.5E+26	3.0E+26	6.1E+26	1.4E+27
0	4.20	5.93	8.53	13.00
30	0.07	0.01	0.00	0.00
60	0.12	0.11	0.00	0.00
90	0.00	0.01	0.00	0.00
120	0.00	0.01	0.00	0.00
150	0.19	0.19	0.00	0.21
180	0.99	1.27	1.68	2.41

Table 2. Normalized maximum particle velocities (to the escape velocity of the Earth (11.2 km/s)) at selected directions. The angles are the angles from the impact point along a great circle.

Two main features emerged from the data set as well as the polar plot (Figure 1): (1) the atmosphere

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directly above the impact point will be tremendously accelerated and the amplitude of the ground motion at this position is the greatest among all directions; (2) ground motions along other directions are not as prominent as the impact point and only the antipodal (180°) direction can sufficiently accelerate the atmosphere column directly above to reach escape velocity, but the fraction of atmosphere reaching the escape velocity is much less.

The escape air stream at the antipodal position was not reported before and it should be present in a direct, non-oblique giant impact with energy above 2.0 x 10^{26} J. However, the fraction of mass reaching the Earth's escape velocity is very limited. Even at the most energetic impact (1.4 x 10^{27} J) in our calculations, the mass of air particle reaching the Earth's escape velocity is about 15% above the impact point and about 0.01% at the antipodal position.

Figure 1 showed the variation of the normalized maximum velocities reached in the atmosphere. There are some minute features, but it closely followed the features in the ground velocity profiles in Ni and Ahrens. This behavior of the atmosphere mimicking the ground motion has been recently observed directly using the Doppler sounding technique [12].

The key issue is now whether the ground motion along will be sufficiently energetic so that the whole Earth's atmosphere can be blown-off. It seems to the authors that ground motion alone is not sufficient to propel the full Earth atmosphere. However, this process is one of the many propelling processes which can significantly accelerate atmosphere to escape the Earth's gravity field. Other processes such as vaporization and bolide-atmosphere interaction may also contribute [5-7]. In addition, the existence of the antipodal position jet stream provides additional sites of launching atmosphere. However, the materials can be blown-off at this position will be very limited due to the severely attenuated ground motion.

References:

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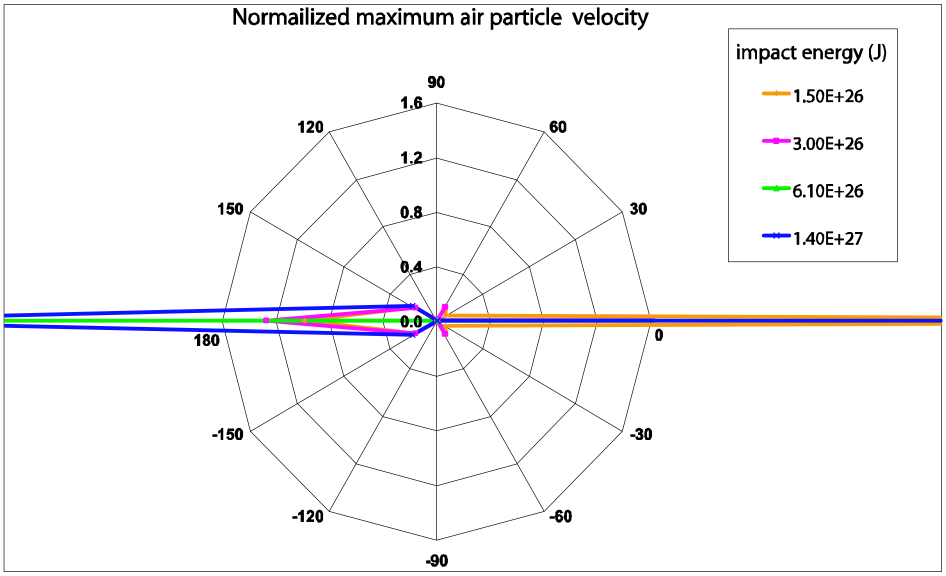

Figure 1 Angular distribution of the normalized maximum air particle velocities achievable at various directions under different impact energy. The radii are the normalized maximum velocity (/Earth's escape velocity 11.2 km/s). Refer to Table 2 for the actual value of each data point.