NUMERICAL SIMULATIONS OF THE CHELYABINSK AND SL9 IMPACTS.

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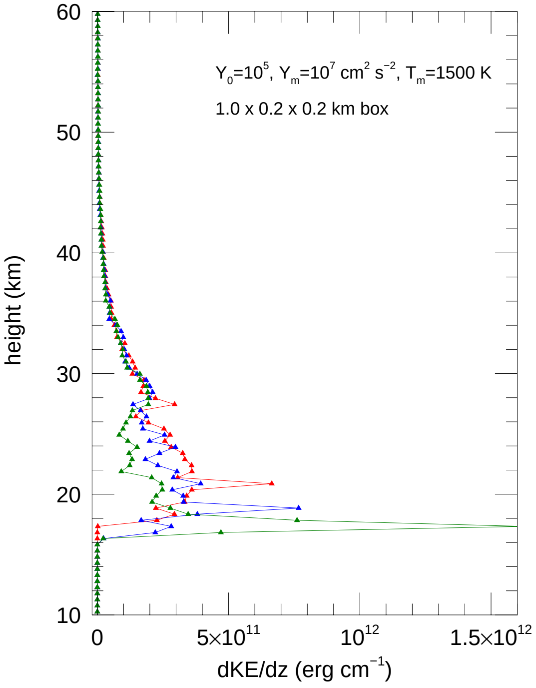

Figure 1: Energy deposition curves $E(z) = dKE/dz$ from three CTH simulations of the Chelyabinsk impact. The impactor is 20 m in diameter and of basaltic composition, impacting at 19.03 km s^{-1}. For the second and third simulation, the initial position of impactor is displaced by half a grid cell (0.63 m) from the first calculation.

Impacts into planetary atmospheres are an important aspect of impact phenomena in general. Planetary atmospheres can serve as shields that absorb the kinetic energy of a bolide, preventing it from striking the surface and depositing the energy here. In the case of the Earth, the atmosphere will (up to a point) prevent casualties and damage to human property.

In recent decades, we have had spectacular opportunities to study a few atmospheric impacts in great detail. Two events stand out: 1) the series of impacts of Comet Shoemaker-Levy 9 (SL9) into Jupiter in 1994 and 2) the airburst over Chelyabinsk, Russia in February 2013. The amount of detailed information gathered about both these events makes it possible to compare theories and modeling to observations. In particular, verification and validation of hydrodynamic modeling can be performed.

Hydrodynamic modeling

This work presents some results from hydrodynamic modeling of the Chelyabinsk and SL9 impacts. The focus is on the profile $E(z) = dKE/dz$ of kinetic energy $KE = 1/2mv^2$ deposition in the atmospheres of the Earth and Jupiter, respectively. One particular phenomenon noted in previous simulations of the SL9 impacts [1] was "chaos" or sensitivity to initial conditions: small changes in the the computational setup (such as displacement of the impactor by a fraction of a grid cell) lead to major (order-unity) differences in the profile of $E(z)$. If this holds true in general, it would have significant implications for predictions of the effects of hazardous impacts on the Earth. Assessments of hazards would have to take the additional uncertainty of the profile into account.

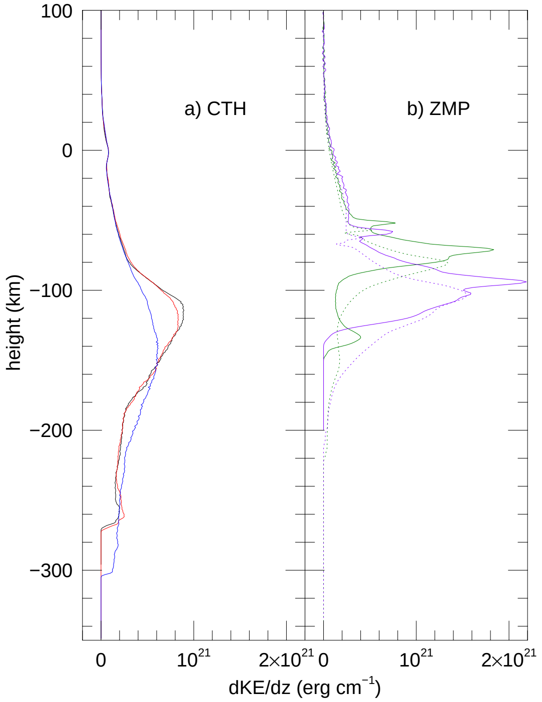

Figure 2: Energy deposition curves from sample SL9 calculations a) CTH b) ZEUSMP. The impactor is 1 km in diameter and made of ice (modeled by ANEOS for the CTH calculations and the Tillotson EOS for ZEUSMP. For the two ZEUSMP calculations the energy deposition curves were calculated in two different fashions: the "past-the-post" method (solid curves) and "box integration" (dotted curves).

The previous calculations of SL9 impacts used the ZEUSMP code[2]. Most of the calculations presented here were done with a different and independently formulated hydrocode, CTH. Developed at Sandia National Laboratory, CTH[3] is a highly advanced code widely used in the planetary science community. It makes use of material strength models and advanced tabular equations of state such as ANEOS and the SESAME library from Los Alamos National Laboratory. We also present some new ZEUSMP SL9 calculations for comparison.

One difference between the older ZEUSMP calculations and the CTH calculations presented here is the analysis of kinetic energy profile. The ZEUSMP SL9 calculations presented a "past-the-post" profile in which the amount of mass, momentum, and kinetic energy that passed a given height z was monitored and used as the basis for the calculation of $E(z)$. In contrast, at the present writing, analysis for $E(z)$ for CTH calculations is done by integrating all mass, momentum, and kinetic energy in the computational domain. Depending on the domain size, this amounts to integrating the energy profile $E(z)$ over the computational domain, leading to a convolution of the profile with a smoothing function whose characteristic scale is the domain size. A processing method that reproduces the past-the-post analysis is being developed at the time of writing.

An additional difference between the old ZEUSMP SL9 calculations and the ones reported here (both ZEUSMP and CTH) is that the new calculations were conducted in a reference frame moving at a constant velocity equal to the initial impact velocity (19.03 km s^{-1} for Chelyabinsk, 61.46 km s^{-1} for SL9). The older calculations were carried out in a variable-velocity frame of reference, in which the computational domain tracked the front end of the impactor material, and thus decelerated in tandem with the impactor.

Chelyabinsk results

Figure 1 shows the results from three sample calculations of the Chelyabinsk impact done with the CTH code. The domain was $1 \times 0.2 \times 0.2$ km in size, and the spherical 20-meter diameter impactor was assumed to have a modest amount of strength ($Y_{max} = 10^7$ cm^2 s^{-1}) and basaltic composition. Grid resolution was eight elements per impactor radius ("R8") Calculations were done with slight (0.63 m) displacements in initial positions, corresponding to half a grid-cell. While the energy deposition curves are consistent with the observations of the light curve [4], sensitivity to initial conditions is also evident, suggesting that the phenomenon applies to other cases in addition to the SL9 environment.

SL9 results

Figure 2 shows results from sample SL9 calculations using CTH (left) and ZEUSMP (right). The impactor is an ice sphere moving at 61.46 km s^{-1} through the Jovian atmosphere starting at a height of 100 km above the 1-bar level of the atmosphere. The computational domains are $105 \times 10 \times 10$ km in size for the CTH calculations and $105 \times 10 \times 10$ km for the ZEUSMP calculation. For both sets of simulations a non-uniform grid was used, with a maximum resolution of 6.25 m (R8). For the two ZEUSMP calculations the energy deposition curves were calculated in two different fashions: the "past-the-post" method (solid curves) and "box integration" (dotted curves). As might be expected the box-integration yields a smoothed curve and one that is displaced to slightly lower altitudes. In contrast to the Chelyabinsk calculations, the computational domain now extends over a large fraction of the region in which energy is deposited, so the smoothing effects of a box integration are apparent. The CTH curves are calculated with a box-integration method. Even after taking into account the differences in energy-deposition calculation methods, differences between the CTH and ZEUSMP simulations are evident. In general the CTH calculations apparently show a broader and deeper energy deposition curve, with significant amounts of energy being deposited below 200 km below the 1-bar level of the Jovian atmosphere. This may be due to effects of using different equations of state for the calculations (ANEOS water-ice for CTH vs. Tillotson for ZEUSMP).

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