MODELING THE CHELYABINSK IMPACT, II. D. G. Korycansky, *CODEP, Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064* .

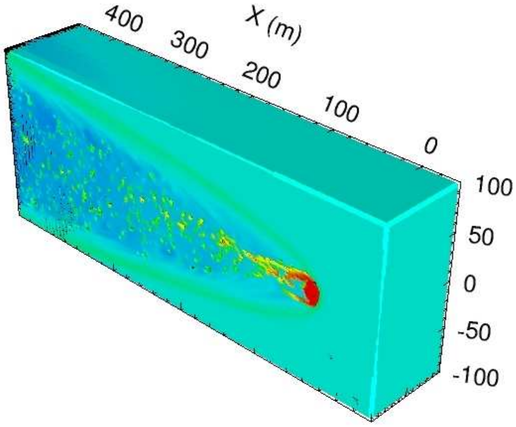

Figure 1: Timestep at $t = 7.5$s ($z = 64$ km) of a CTH simulamtion of the Chelyabinsk impact. Density is shown on a logarithmic scale ($10^{-8} < \rho < 1$ gm s^{-3}). Simulation parameters include moderate resolution (R6.25) in a domain of size $0.5 \times 0.2 \times 0.2$ km. The impactor is modeled as basalt sphere of 20 m diameter with zero material strength.

On February 15th, 2013, a large meteor entered the atmosphere over the Chelyabinsk, Russia. Although it did not strike the Earth's surface, the blow-up of the object was impressive. There were numerous witnesses (cf. youtube videos provided in many cases by dashboard-mounted cameras in vehicles), and the fireball was seen over several Russian cities. A good deal of damage was done by the shock wave from the exploding bolide: broken window glass in buildings and numerous injuries therefrom, although fortunately no fatalities seem to have occurred. The impact was likely the largest known event since the Tunguska impact over a century ago.

Subsequent analysis of the event, including orbit analysis and recovery of meteorite fragments, suggest that the impactor was $\sim 17 - 20$ m in diameter, striking the atmosphere at 18.6 km s^{-1} at an angle of 75 degrees from the vertical [1]. The object composition was chondritic of the LL5 type [2] with a bulk density of ~ 3.3 gm cm^{-3}. Further discussion and analysis of the impact observations can be found in the discussion by [3].

The event underscores the potential hazard posed by the impact of asteroids on the Earth. Even non-fatal impacts of small objects can cause significant amounts of damage. As such, these events need to be understood and the hazards they pose need to be characterized for mitigation purposes.

Beyond the hazard aspect, terrestrial meteor impacts are a fascinating example of complex physical processes in the natural world. They present strong challenges for modeling of the type described in this abstract. At the same time, the wealth of data generated by these events, and this one in particular,

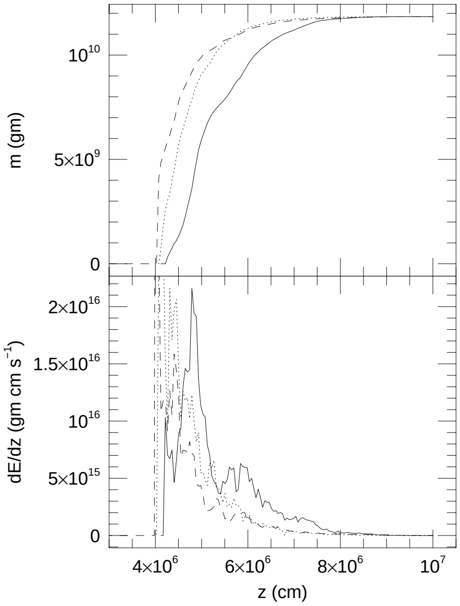

Figure 2: Plot of mass (top) and kinetic energy deposition (dE/dz) as a function of height for three low-resolution trials for which impactor strength was varied: solid line, zero-strength; dotted line: strength $Y = 10^9$ dyne cm^{-2} ; dashed line: strength $Y = 10^{11}$ dyne cm^{-2} .

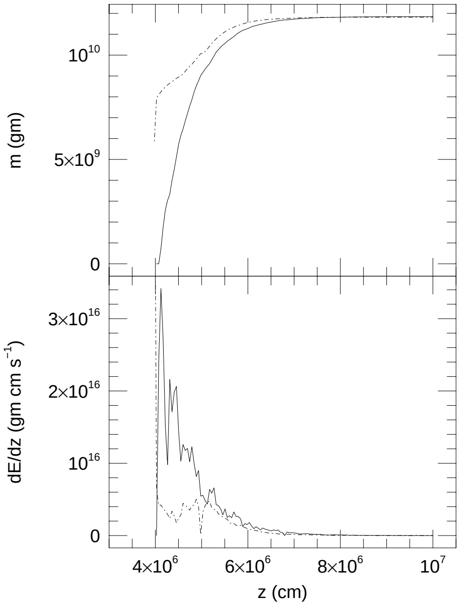

Figure 3: Plot of mass (top) and kinetic energy deposition (dE/dz) as a function of height for two trials for which resolution was varied: solid line, R3.125; dotted line: R6.25.

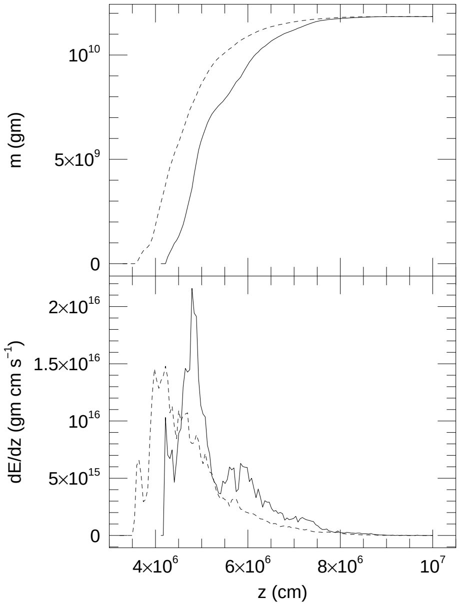

Figure 4: Plot of mass (top) and kinetic energy deposition (dE/dz) as a function of height for trial trials for which computational domain was was varied: solid line, domain size $0.5 \times 0.2 \times 0.2$ km; dotted line, domain size $1 \times 0.2 \times 0.2$ km.

afford a unique set of tests: literal "ground truth" applications of modeling techniques. Given the parameters of the event (object size, velocity, impact angle, composition, and material properties), it should be possible to match the observations, in particular the energy deposition along the bolide's track.

Hydrodynamic modeling

Simulation of the Chelyabinsk impact is challenging. Modeling an object of this size demands high resolution (grid cells Δx of order a meter or smaller); combined with the velocity v_i of the impact, the Courant condition for the simulation requires timesteps $\Delta t \leq \Delta x/v_i \sim 10^{-5}$ s. The challenge is increased by the high inclination of the bolide's path, which increases the timescale of the event by a factor ~ 4 from a vertical impact starting at $z = 100$ km height, to ~ 10 s, thus requiring approximately 10^6 timesteps for a single calculation.

We report results from attempts at modeling the impact using the CTH hydrocode at low-to-moderate resolution (grid cells Δx 1.5–3 m in size). Developed at Sandia National Laboratory, CTH[4] is a highly advanced code widely used in the planetary science community. It utilizes adaptive mesh refinement to concentrate computational resources at locations of physical interest in the simulation, such as shock fronts and material interfaces. In addition, 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.

The impactor is modeled as a 10-meter radius basalt sphere moving at $v_i = 18$ km s^{-1}, into an atmospheric profile (vertical scale height $H = 10$ km) at an impact angle of 74° from the vertical). We use the SESAME equation of state with a basic material strength model (GEO) that is included in CTH. The impact initial height at $t = 0$ is $z = 100$ km. In this calculation we find the impactor loses mass and energy primarily by ablation as opposed to fragmentation to large pieces, hydrodynamic instability or spreading by aerodynamic pressure gradients ("pancaking"). Fig. 1 shows density on a logarithmic scale along one of the mid-planes of the computation. We have run six cases so far, testing various combinations of material strength model, resolution, and computational domain size. The baseline case is one in which the impactor has zero strength and the domain is $0.5 \times 0.2 \times 0.2$ km in size. The impactor is made of basalt as modeled using the SESAME EOS. The maximum resolution is $\Delta = 3.2$ m or 3.125 resolution elements for the impactor radius of 10 m ("R3.125" resolution).

Figs. 2-4 show the mass m in the computational domain (the "box") , along with the kinetic energy deposition deposition dE/dz, where $E = mv^2/2$ is the kinetic energy. The quantities are plotted as function of (true) height z above the ground. The three different plots are tests of physical and computational parameter relative to changes from the baseline case. In Fig 2, the effects of impactor material strength are shown with cases for maximum material strength $Y = 0$, 10^9, and 10^{11} dyne cm^{-2}. (In the latter two cases loss of strength occurs at $T = 1500$ K in the material.) In Fig 3, the baseline case is compared against one with 2× higher resolution (R6.25). Finally in Fig 4, the effects of increasing the domain size to $1 \times 0.2 \times 0.2$ km are shown. In general, the effects of including the (more realistic) properties in the calculation–especially computational properties of higher resolution and larger domain–lead to the impactor penetrating farther down into the atmosphere with maximum energy deposition at a lower height (~ 40 km opposed to 50 km). It seems likely that both aspects of the simulations still need improvement before convergence is reached for those properties.

Acknowledgments

The work was supported by NASA Planetary Atmospheres Program award NNX11AD87G and NSF Planetary Astronomy award AST-1109729. DK thanks K. Zahnle for allocation of time on a 12-processor workstation.

References

[1] Yeomans and Chodas 2013. `http://neo.jpl.nasa.gov/news/fireball_130301.html` [2] Kohout *et al.* 2014 *Icarus* **228**, 78. [3] Borovicka *et al.* 2013, *Nature* **503**, 235. [4] McGlaun, J. M., et al., 1990. *Int. J. Impact Engr.* **10**, 351-360.