MODELING THE CHELYABINSK IMPACT. D. G. Korycansky, *CODEP, Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064* , C. Palotai, *Department of Physics, University of Central Florida*.

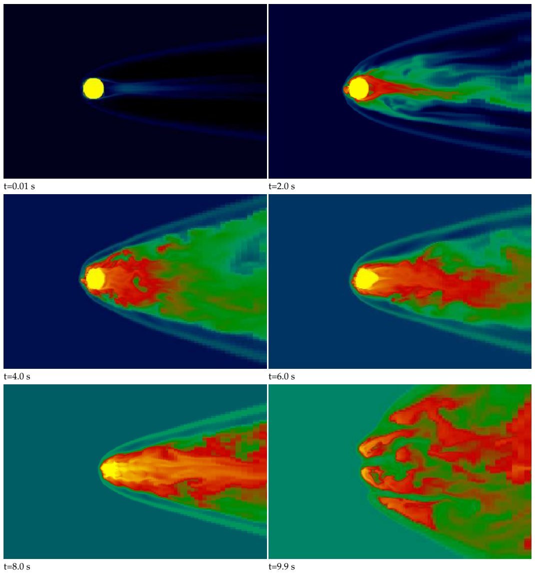

Figure 1: A ZEUSMP2 simulation of the Chelyabinsk bolide. Density is shown in mid-plane slices at times $t = 0.01$, 2, 4, 6, 8, and 9.9 s after the initial start of the calculation.

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, 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.

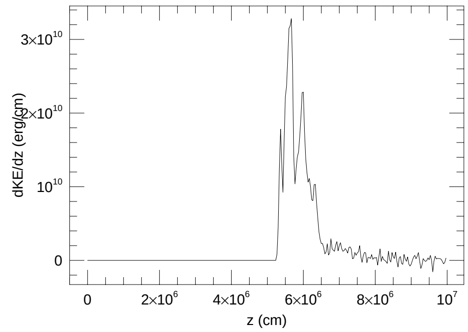

Figure 2: Energy deposition curve (erg cm^{-1}) for a simulation like that shown in Fig. 1.

Hydrodynamic modeling

We have carried out some low- to medium-resolution three-dimensional calculations with the ZEUSMP2 hydrodynamics code [4] that we have successfully used for a number of studies of atmospheric impacts for objects in the size range from tens of meters to kilometer scales, primarily for impacts into the atmospheres of Venus and Jupiter [5-8].

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.

The ZEUSMP2 code has several features that aid in this calculation, for instance the ability to include a moving grid that follows the bolide so that it does not have to be advected through an inordinately long grid. The code's chief weakness as presently configured is the lack of a strength model for solid materials. While this lack may not affect simulations of km-scale bodies previously modeled [5-8], it may be expected that material strength would be more important for smaller bolides like the Chelyabinsk object.

Figs. 1 and 2 show images and energy deposition for two separate Chelyabinsk simulations; Fig. 1 shows density

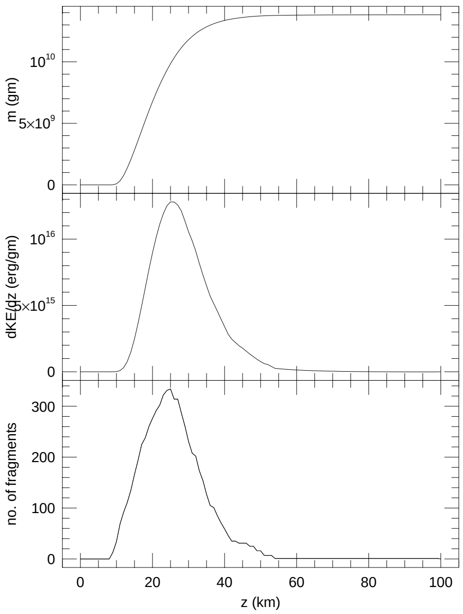

Figure 3: Chelyabinsk impact according to fragment-model equations. Ablation coefficient $C_A = 1.0$, Drag coefficient $C_D = 1.0$, fragment velocity coefficient $C_V = 1.0$, nominal strength $\sigma_0 = 10^7$ dyn cm^{-2}, for nominal mass $m_0 = 10^{10}$ gm, strength power-law index $\gamma = 0.5$.

in the mid-plane for a simulation with "R16" resolution, i.e. minimum grid-cell size=62.5 cm at the indicated times: $t = 0$ corresponds to an initial altitude of 100 km. Fig 2. shows the energy deposition dE/dz where $E(z)$ is the kinetic energy of bolide material. The peak deposition is between 50 and 60 km altitude, compared to the observed peak at ~ 30 km [3]. The discrepancy is probably due to the lack of a strength model in the ZEUSMP2 code, as mentioned, that causes the model impactor to disintegrate at too high an altitude.

Simplified model with fragmentation

As noted above the ZEUSMP2 calculations appear to deliver incorrect results in this case, as judged by energy deposition curves like those shown in Fig. 2. Another model we discuss here is one in which the impactor is considered in terms of discrete object(s) subject to ablation, drag, and fragmentation. This model is essentially the "separated fragment" model discussed by other authors [9,10], as well as being used by us for modeling the production of crater populations and Venus and Titan [11].

For each object (original bolide or fragment) j, we integrate the mass equation

$$\dot{m}_j = -C_A \rho(z_j) A_j v_j, \tag{1}$$

where C_A is the ablation coefficient, $A_j = \pi d_j^2/4$ is the cross-section for an object of diameter d_j, $\rho(z)$ is the atmosphere density at height z, and the speed $v_j = (v_x^2 + v_y^2 + v_z^2)_j^{1/2}$. The velocity of the bolide $\mathbf{v}_j = (v_x, v_y, v_z)_j$ is determined by

$$m_j \dot{\mathbf{v}}_j = -C_D \rho(z_j) A_j v_j \mathbf{v}_j - g m_j \hat{z}_j, \tag{2}$$

where C_D is the drag coefficient and g is the Earth's gravity. We model the impactor (and fragments) as quasi-cylinders of constant density ρ_i and initial length $h = 4m_j/\pi\rho_i d_j^2$. Mass loss by ablation is assumed to reduce d_j while keeping h and ρ_i constant. Finally the object's position $\boldsymbol{x}_j$ is given by $\dot{\boldsymbol{x}}_j = \mathbf{v}_j$. In our previous work [11] we included "pancaking" or flattening of the impactor by aerodynamic forces but we neglect that here assuming that objects have non-negligible strength. We had also previously assumed that strengthless bodies fragmented due to Rayleigh-Taylor instability driven by deceleration, but bolides in this size range (tens of meters) are more likely to fragment due to dynamic pressure across a body with material strength σ. Here we assume that material strength is mass-dependent according to $\sigma = \sigma_0 (m/m_0)^{-\gamma}$, so that a body m_j will fragment into $2 < n < 7$ sub-masses m_{j+n} smaller objects, with masses and small transverse velocities chosen from random values chosen as with previous modeling [11].

A calculation starts with a single object at the initial height $z = 100$ km, and proceeds by integrating equations 1 and 2 until the dynamic pressure $\rho(z_j)v_j^2 = \sigma$, at which point the aformentioned fragmentation prescription is applied. Individual fragments are then integrated downards, with an indefinite number of sub-fragmentations permitted until all objects have ablated or been halted (i.e. have velocities less that 10^{-3} the velocity of the initial object). Fig. 3 shows results from a run with nominal values $C_A = C_D = C_V = 1.0$, $\sigma_0 = 10^7$ dyne cm^{-2}, $m_0 = 10^{10}$ gm, and $\gamma = 0.5$. Peak energy deposition is reached at an altitude of 25-30 km, similar to the inferred value of ~ 30 km [3]. Further work on this problem will explore the effects of different parameter values and will compare results with the observations to constrain the physical properties of the bolide.

Acknowledgments

The work was supported by NASA Planetary Atmospheres Program award NNX11AD87G and NSF Planetary Astronomy award AST-1109729.

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] Hayes *et al.* 2006, *Ap. J. Supp.* **226**, 99. [5] Korycansky and Zahnle 2003, *Icarus* **161**, 244. [6] Korycansky *et al.* 2006 *Astrophys. J.* **646**, 642. [7] Palotai *et al.* 2011, *Astrophys. J.* **731**, # 3. [8] Pond *et al.* 2012, *Astrophys. J.* **745**, # 113. [9] Artemieva and Shuvalov 2001, *J. Geophys. Res.* **106**, 3297. [10] Bland and Artemieva 2003, *Nature* **424**, 288. [11] Korycansky and Zahnle 2005, *Plan. Space Sci.* **53**, 695.