THREE-DIMENSIONAL SIMULATIONS OF OBLIQUE ASTEROID IMPACTS INTO WATER.
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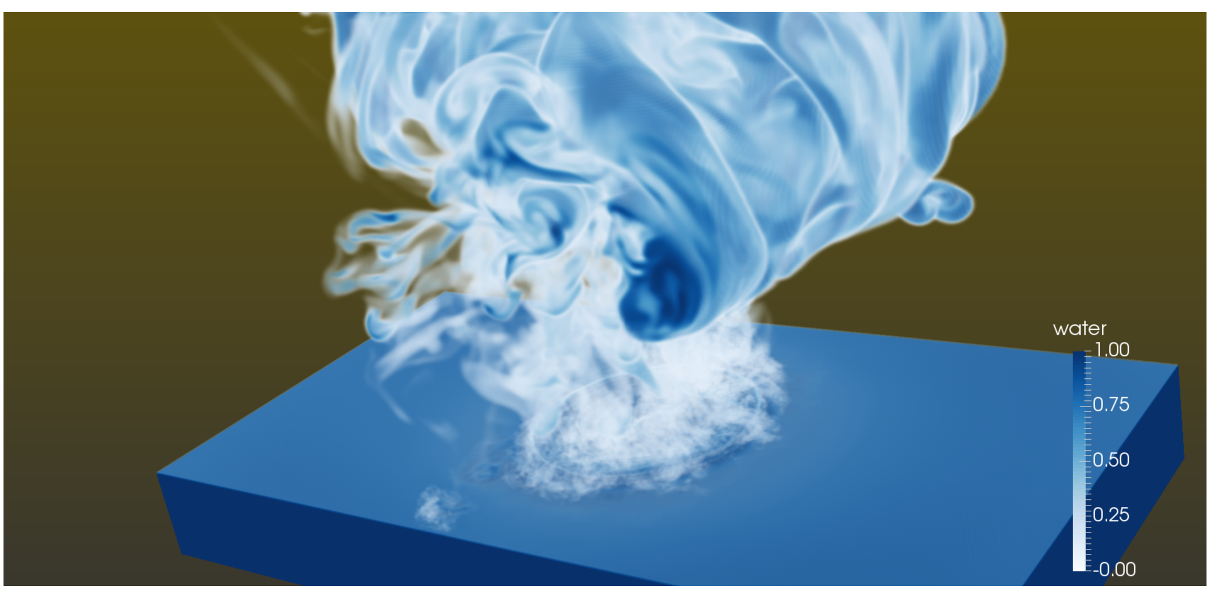
Waves generated by impacts into oceans may represent the most significant danger from near-earth asteroids and comets. For impacts near populated shores, the crown splash and subsequent waves, accompanied by sediment lofting and high winds, are more damaging than storm surges from the strongest hurricanes. Asteroids less than 500m in diameter striking deep water far from shores may produce waves detectable over large distances, but these waves are probably not significantly dangerous.

We present a suite of 11 new three-dimensional simulations of oblique impacts into deep water, with trajectory angles ranging from 20 degrees to 60 degrees (where 90 degrees is vertical). These simulations are performed with the Los Alamos Rage hydrocode, and include atmospheric effects including ablation and airbursts. These oblique impact simulations are specifically performed in order to help determine whether there are additional dangers from the obliquity of impact not covered by previous two-dimensional studies. Water surface elevation profiles, surface pressures, and depth-averaged mass fluxes within the water are prepared for use in propagation studies.

An ocean impact within ten to twenty kilometers of a populated coastline would be devastating. The crown splash reaches many kilometers into the air. Water descending on ballistic trajectories from the crown splash could destroy infrastructure and produce severe flooding. The jet that rebounds from the transient crater can rise a kilometer or more; its collapse then generates a series of gravity waves that can propagate. Near shores, something akin to a storm surge would result, accompanied by hurricane force winds and lofted sediment from the nearby seafloor. High temperatures generated by the disintegration of the asteroid and an intense pressure wave will be destructive to lives and property on shore. In the case of an airburst occuring prior to or instead of an impact, the resulting shock waves will also be locally destructive, as witnessed in the Chelyabinsk event of 2013 and the Tunguska event of 1908.

Because asteroid impacts produce high-amplitude but short waves, propagation into the far field is not expected to be efficient. This conclusion is supported by wave-propagation studies. Airbursts produce pressure fields over wider regions, and had been thought capable of generating propagating waves, but the amplitudes are much lower than in direct impacts, and the wavelengths are not significantly longer.

A large fraction of the impacting asteroid's kinetic energy is consumed by the vaporization of water from the transient crater. The figure below is a volume rendering of water mass fraction 94 seconds after the impact of a 250-meter diameter asteroid into an ocean of



5 km depth. The transient water crater produced in this simulation was 1 km deep and 3 km wide. at maximum extent. A considerable fraction of the water in that crater was vaporized and buoyantly lofted into the stratosphere. While water vapor in the troposphere regularly rains out, in the stratosphere it can linger for months to years. Because water vapor is a potent greenhouse gas, there may be significant regional effects on climate.

The range of impactor size considered, namely 100m to 500m diameter asteroids, is found (as expected) to bracket the threshold for danger being considered by the ongoing near-earth asteroid search programs being conducted by NASA and other national and international agencies. The ongoing searches for hazardous near-earth objects should continue to aim for completeness down to 140m diameter.

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