IMPACT VAPOR PLUME EXPANSION AND HYDRODYNAMIC COLLAPSE IN THE SOLAR NEBULA.

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Introduction. Collisions are a major physical process during planet formation. Vaporization has long been recognized as a key aspect of giant impacts between planetary embryos. In contrast, vaporizing collisions between planetesimals has not been studied in detail. Furthermore, the effects of impact vaporization on the final chemical and physical properties of the surviving planetary bodies are not fully understood.

Using recent shock thermodynamics experiments and planet formation simulations, we have revised the criteria for vaporization of planetary materials by collisions in the protoplanetary disk [1] and shown that vaporizing collisions between planetesimals is an important process [2]. Shock-induced vaporization is different than vaporization by heating under quasi-static conditions. Shock waves, and the sound waves that release the pressure, also transfer momentum. As a result, the thermodynamic path for vaporization during decompression from a shock state imparts a specific direction and magnitude to the material velocity that affects the subsequent dynamics of the system.

Here, we investigate the coupled thermodynamics and hydrodynamics of vaporizing collisions in the solar nebula. We find previously unrecognized phenomena that demand a reassessment of impact processes during the early stages of planet formation.

Impact Simulations. We conducted 2D and 3D simulations of vaporizing collisions between planetesimals using the multi-material, adaptive-mesh, Eulerian shock physics code, CTH v11.0 [3], using wide-ranging equations of state for water [5-Phase EOS, 4], forsterite [M-ANEOS, 5], iron [ANEOS, 6], and hydrogen [SESAME 5250, 7]. Lagrangian tracer particles were embedded into the bodies and nebular gas to track their thermal histories and locations. The simulations were purely hydrodynamic and did not include gravity because the impact velocities exceed both the gravitational escape velocities and the critical velocities for disruption of 100-km scale planetesimals. We neglected radiative cooling of the vapor plume because most of the system is optically thick during plume expansion and collapse.

Vapor Plume Results. Although the details of vapor plume interactions with nebular gas depend on the specific impact conditions, the following description applies to the example shown in Fig. 1 and generally to vaporizing collisions between planetesimals. The supersonic expansion of the vapor plume drives an asymmetric bow shock into the surrounding nebular gas (5 min). Vaporization of only a few wt% of material leads to many orders of magnitude increase in volume [1]. Initially, the densities in the plume are larger than in the shocked nebula, which drives a hydrodynamically stable plume boundary. But, as the outward flow continues, the pressures and bulk densities at the boundaries of the plume become smaller than in the adjacent shocked nebula (0.4 hr), both from volume expansion and from condensation during decompression. The low pressures in the plume are hydrodynamically unstable, and secondary pressure and shock waves are generated to slow and then quickly reverse the flow. For the geometry in Fig. 1, flow reversal occurs primarily along the plume boundaries that are perpendicular to the vector formed by the leading edge. During plume collapse, shock-heated gases, laden with condensates coupled to the gas, hydrodynamically flow inwards and mix with the planetesimal material over several hours. The impact creates a cloud of warm gas and condensates (dust and melt) in the nebula.

Discussion. The vapor plume and bow shock generated by a vaporizing collision dynamically displaces the solar nebula. The expanding vapor plume evolves to become a large unstable region in the nebula that hydrodynamically collapses on timescales controlled by the sound speeds of the gases.

The melts in the vapor plume are sheared apart by the surrounding gas [8]. Only the small size fraction of melt droplets that couples to the inward flowing gas will be collected in the collapsing plume, and any larger size particles will continue on outward trajectories. [8] finds that the size of melt droplets is primarily controlled by the gas density and that mm-sized and smaller droplets will be concentrated in the collapsed cloud.

Convergence of inflowing gas leads to secondary shocks that thermally reprocess the collected droplets and dust. The thermal history of material in the cloud is complex, with multiple pulses of heating and variable cooling rates. The evaporated planetesimal components in the warm cloud recondense on timescales governed by radiative cooling [9].

Conclusions. We have identified new phenomena that occur during vaporizing collisions in the nebula that are different than collisions without a surrounding gas [10]. Analytic descriptions of collision outcomes must be re-evaluated to account for shearing with nebular gas and vapor plume collapse. The cloud of warm gas, laden with dust and melt droplets, has the potential to form new planetesimals [9] with characteristics similar to chondritic meteorites [11].

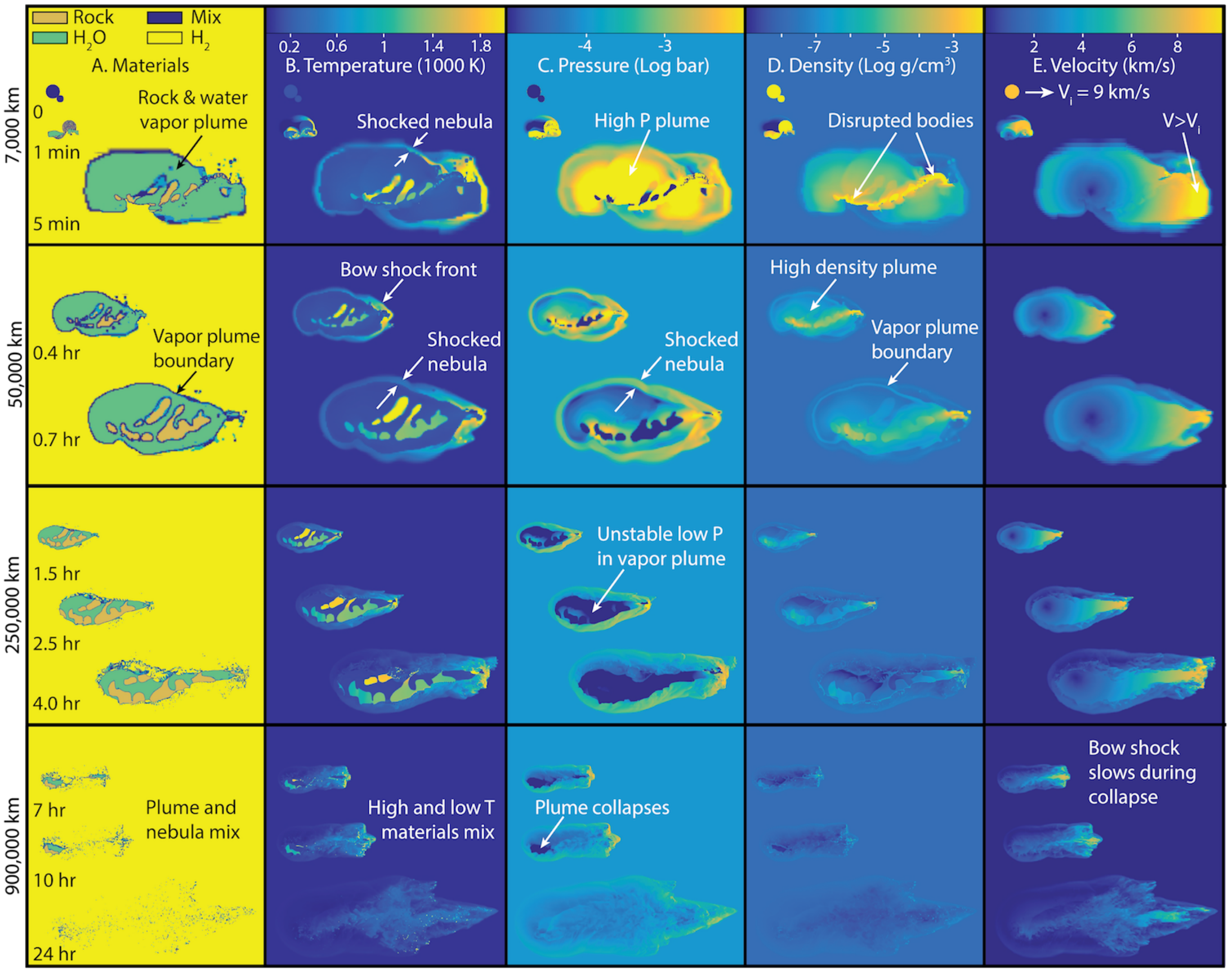

Fig. 1. Impact vapor plume expansion and collapse in the presence of the solar nebula forms a cloud of warm gas laden with melt droplets and dust. Time sequence for a collision between 36% porous, 250 K ice-rock planetesimals (17 wt% ice) calculated using the CTH hydrodynamics code in 3D. A 200-km radius body collides with a 100-km radius body at 9 km s^{-1} and 45 degrees. Columns A-E show materials, temperature, pressure, density and velocity contours in the equatorial plane of both bodies, and the length scale for each row indicates the height and width of each panel. The smaller body begins in the frame of reference of the nebular hydrogen gas, at 200 K and 10 Pa (10^{-4} bar). Decompression and expansion accelerate the vapor plume, driving a bow shock that dynamically displaces and thermally processes a volume of the solar nebula several orders of magnitude larger than the original bodies. Numerical suppression of mixing leads to the artificially distinct zones of water and rock vapor within the plume. Dark blue in column A indicates mixed composition cells with a second material exceeding 0.1 vol%. Materials derived from both the nebula and the planetesimals are size-sorted and mixed during plume collapse [8]. Dense clumps in the warm cloud may form new planetesimals on timescales of several days to weeks [9].

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