COLLAPSING IMPACT VAPOR PLUME MODEL FOR CHONDRULE AND CHONDRITE FORMATION

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Introduction. Undifferentiated meteorites, called chondrites, are considered the building blocks of planets. They are comprised of various proportions of chondrules, grains of Fe-Ni metal, and a fine-grained matrix. Chondrules are mm-sized silicate spherules that were transiently heated to partial or complete melting. They are evidence for widespread thermal processing of material in the solar nebula during the time period of planetesimal formation. In spite of their importance, there is no consensus on the principal physical mechanism that formed chondrules because no single process is able to satisfy all of the observed characteristics of chondrites [1, 2], and multiple processes may be required.

Collisions have been proposed repeatedly as instigators of chondrule formation and criticized repeatedly as being incompatible with meteoritic observations [1, 2]. Collisions were a ubiquitous process during planet formation that altered the thermal and mechanical structure of planetary bodies, and yet most collision processes are not understood at the level of detail needed to compare to geochemical and thermal constraints from meteorites.

Here, we develop a physical model for chondrule formation based on new results on multiple aspects of vaporizing collisions between planetesimals. Several papers at this meeting support this work [3-8]. The model is centered on (i) the discovery of previously unrecognized phenomena initiated by collisions that occur in nebular gas and (ii) the demonstration that vaporizing collisions between planetesimals are triggered by the growth and migration of planets. The model offers new pathways toward addressing the strongest criticisms of impact production of chondrules.

Collapsing vapor plumes in the solar nebula. We modeled vaporizing collisions between planetesimals in the presence of nebular gas [8]. The adiabatically expanding vapor plume drives a bow shock that dynamically displaces the solar nebula. Driven by the momentum of the outward flow, the plume expands to vapor pressures below that of the surrounding nebula. The low-pressure plume is an unstable region in the nebula, and secondary waves develop to reverse the outward flow. The plume collapses by hydrodynamic inflow of gases on timescales controlled by the sound speeds of the gases. The volume of nebula disturbed by the impact event is many orders of magnitude larger than the original volume of the colliding planetesimals. During the collapse of the plume, nebular gas and dust are mixed with materials from the original planetesimals [Fig. 1 in 8].

Size limit for melt and dust in the collapsing plume. The size of molten fragments in the vapor plume was investigated by considering the balance between shear forces and surface tension [7]. Molten fragments above a critical size are broken down into smaller sizes by shear with the surrounding gas. Only the size fraction of condensates that couples to the gas will be collected by the reversing flow of the collapsing plume. Any particles that are too large to couple to the reversing flow will continue on outward trajectories. The size limit for coupling is primarily controlled by the gas density. Based on the analysis in [7], we find that mm-sized and smaller particles will be concentrated by the collapsing cloud.

Free-floating nebular debris that are small enough to couple to the collapsing vapor plume will also be incorporated into the cloud, and some nebular dust will be melted by the hottest regions in the bow shock to form melt spherules from nebular material.

We find that vapor plume expansion and its subsequent collapse create size-sorted silicate melt droplets that are consistent with the sizes of chondrules. The maximum droplet size in the cloud is primarily controlled by the density of nebular gas [7].

Warm clouds of gas, chondrules, and dust. The vaporizing collision creates a cloud of shock-heated gas that is enriched in mm-size and smaller chondrules and dust. The warm gas is a mixture of nebular gas and components evaporated from the planetesimals. The material collected by the collapsing plume experienced a range of shock processing, from strong shocks that partially vaporized the silicates to weak shocks that did not initiate melting. Strongly shocked materials from the planetesimals initially expand adiabatically and cool quickly. However, these materials are reheated by secondary shocks that are generated in the collapsing vapor plume. The secondary shocks, and the bow shock in the nebula, are followed by slower and more varied cooling rates compared to cooling from the primary impact shock. In our simulations [8], the range of cooling rates experienced by materials in the cloud overlaps with the range inferred for chondrules [2].

We also estimated the number density of chondrules in the collapsed plume [4]. We find that dense clumps in the plume satisfy the number density inferred for the origin environment of chondrules based on geochemical and isotopic constraints [9, 10].

Occurrence of vaporizing collisions between planetesimals. Using the results from recent shockwave experiments, we re-calculated the criteria for the onset of vaporizing collisions [6]. We find that the required impact velocities are modest (e.g., 1-6 km s^{-1}). Multiple effects lead to lower critical impact velocities for vaporization, including higher initial temperatures and release into lower ambient pressures. Porosity in the colliding bodies also affects the degree of vaporization.

Because chondrites represent a primitive composition, we investigated the range of possible mutual collision velocities between a population of planetesimals. We find that, during the growth of the gas giant planets, nearby and resonant planetesimals can be dynamically excited to the critical impact velocities for vaporization [e.g., 11-12]. We also show that giant planet migration can incite vaporizing collisions in the asteroid belt and terrestrial planet forming regions [3]. These vaporizing collisions would have occurred in the presence of nebular gas and would have been initiated at specific times and locations that depend on the history of the giant planets.

Vaporizing collisions after the dispersal of nebular gas have different dynamic and thermochemical outcomes as the ejecta expands and cools into vacuum [5]. Without the nebular gas, there is no reversal of the ejecta plume expansion and the impact debris would not be concentrated or sorted in size.

Formation of new planetesimals from the warm chondrule cloud. The formation mechanism for chondrules must be compatible with sedimentary accretion of chondrules and dust such that bulk chondritic compositions are created.

Our model is based on collisions within populations of primitive planetesimals during the growth of planets. The formation mechanisms and compositions of the original planetesimals are an active area of research [13-15]. We modeled collisions between porous dust aggregates that approximate chondritic compositions [8]. Vaporizing collisions thermally and mechanically reprocess the original planetesimals to form a cloud of similar composition.

The warm cloud of chondrules and dust is a thermal and dynamical anomaly in the nebula [4]. The bow shock and hydrodynamic collapse of the vapor plume impose a velocity field over a large region that is distinct from the background turbulence in the nebula. In addition to the dynamical disturbance, the region must recover from the thermal perturbation. The shock-heated gases are laden with dust and droplets that are dynamically coupled, so the bulk density of the cloud is heavier than the surrounding nebula. As a result, the cloud will not mix with the colder nebula by convection, and the optically-thick cloud will radiatively cool.

Radiative cooling leads to a substantial volume contraction as the gas density in the cloud increases. The surrounding colder nebula will maintain pressure equilibrium with the cloud by flowing inwards. Over days to weeks of radiative cooling, the convergent flow pattern of the surrounding nebula inhibits the dispersal of the dust and chondrules in the cloud and maintains the distinct local chemical environment. Thus, the warmest regions of the cloud are protected from nebular turbulence and aided in gravitational contraction to form new planetesimals [4].

In our model, the energy of collisions can be harnessed for chondrule formation in a manner that leads to assembly of bodies of bulk chondritic composition by the formation of new planetesimals directly from the materials in a collapsed vapor plume. The collapsed vapor plume environment will also be investigated for the potential to explain chemical complementarity between chondrules and the matrix.

Conclusions. We have developed a new physical model for the formation of chondrules and chondrites. Mutual collisions between dynamically excited planetesimals produce impact vapor plumes that collapse and concentrate a size-sorted mixture of chondrules and dust. The warm cloud of shock-heated gas, dust, and chondrules is a dynamical and thermal anomaly in the nebula with characteristics that assist with new planetesimal formation. Our model addresses many of the long-standing criticisms for an impact origin of chondrules by identifying previously unknown aspects of collision processes in the solar nebula.

Acknowledgements: This work is supported by the Sandia Z Fundamental Science Program and DOE-NNSA grant DE-NA0002937; NASA grant NNX15AH54G; NASA grant NNX16AP35H (EJD); and UC Office of the President grant LFR-17-449059. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Prepared by LLNL under Contract DE-AC52-07NA27344.

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