COLLAPSING IMPACT VAPOR PLUMES: A NEW PLANETESIMAL FORMATION ENVIRONMENT.

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Introduction: The timings of iron meteorite parent body differentiation and chondrule formation demonstrate that planetesimal formation was an ongoing process throughout the lifetime of the solar nebula. Multiple mechanisms for planetesimal formation may have acted during this time period [1]. Each mechanism must overcome the meter size barrier, where aerodynamic drag from the nebula induces rapid inward drift of m-sized objects [2], to form kilometer-scale bodies. Bodies larger than order 1-km in size may establish Keplerian orbits in the disk. The formation of chondrite parent bodies must concentrate dust and mm-sized chondrules into self-gravitating >1-km-sized bodies in a manner that overcomes the turbulence in the protoplanetary disk that inhibits the formation of dense regions of small solids [e.g., 3].

Here, we introduce a new environment for planetesimal formation: a dense cloud of warm gas, dust, and melt droplets that is created by a vaporizing collision between planetesimals. The cloud is a dynamical and thermal anomaly in the solar nebula formed by vapor plume expansion and collapse [4]. Vaporizing collisions form the basis for a new physical model for the formation of chondrules and chondrite parent bodies [5]. In this work, we examine the processes that assist the formation of new planetesimals within the collapsed vapor plume.

Our proposed planetesimal formation environment pertains to the assembly of later generations of planetesimals, as it relies upon energetic collisions between pre-existing planetesimals. Primitive planetesimals were present during the initial growth of planets. When excited by growing or migrating giant planets, planetesimals attain large orbital eccentricities and large relative velocities that induce partial vaporization [6,7]. When a vaporizing collision occurs within the nebula, the supersonic expansion of the vapor plume drives a bow shock into the surrounding nebular gas. The momentum of the expansion leads to vapor pressures in the plume that are lower than in the surrounding nebula, and the plume becomes hydrodynamically unstable. Secondary pressure and shock waves develop to reverse the flow, and the vapor plume collapses via a converging inward flow of shocked gases. Refer to Fig. 1 in [4] for an example of vapor plume evolution.

Size-sorting and mass concentration mechanisms: Initially, the melt fragments in an impact-generated vapor plume span a range of sizes. By considering the balance of shear forces and tension, [8] find that large melt fragments are sheared apart and the maximum size of liquid droplets is set by the reversing flow of the vapor plume. Only particles small enough to couple to the gas will be collected by the reversing flow of the collapsing plume, and larger particles will continue on outward trajectories. The maximum size of coupled particles is most sensitive to the gas density, and for the gas densities expected in the nebula, we find that mm-sized and smaller particles (both melt droplets and dust) will be coupled to the inward flow and concentrated by the collapsing cloud. Given the hours to days timescales for vapor plume collapse after collisions between 10's to 100's km sized planetesimals, we expect that most of the original planetesimal material in the plume was sheared to small sizes and coupled to the collapsing cloud.

The reversal of the vapor plume boundary leads to convergent collapse onto a quasi-centerline of the impact plume. Typically, opposite sides of the plume converge at supersonic velocities, generating secondary shocks that arrest the inflowing gas. The sudden change in velocity of the gas leads to shear with the inflowing dust and droplets. To estimate the spatial concentration of the condensates in the collapsing plume, we calculated the stopping distance for mm-sized droplets.

For 1-mm droplets and a shocked gas density of 10^{-4} kg m^{-3}, the droplet is slowed to a relative velocity of 10 m s^{-1} over a timescale of 100's seconds [9]. This stopping timescale is weakly sensitive to the initial differential velocity. The corresponding stopping distance for an initial velocity difference of 2 km s^{-1} is about 30 km. This calculation estimates the stopping distance at both the reversal of the outward flow of the plume and at the points of convergence of the collapsed plume. The stopping distance is orders of magnitude smaller than the sizes of vapor plumes generated by collisions between >~km-sized planetesimals. We infer that small condensates will be efficiently coupled to the flow and concentrated in the plume boundary during collapse and near the quasi-centerline of the fully collapsed plume.

In general, the leading edge of the plume still has momentum as the boundaries perpendicular to the centerline of the plume collapse (see Fig. 1E in [4]). Depending on the impact parameters, the leading edge is also a region that has a high concentration of melt droplets. Overall, we expect the quasi-centerline of the collapsed plume to have an enhanced concentration of dust and droplets.

The collapsing plume is a turbulent environment. Eddies in the flow lead to clumping of the entrained condensates. In our example hydrodynamic calculations of collisions between 100-km scale bodies [4], after 24 to 48 hours, we estimate that the regions with the highest concentrations of melt droplets have bulk densities that exceed 0.001 kg m^{-3}. These regions contain sufficient mass to form new planetesimals 10's km in size.

Nebular dust and debris small enough to be coupled to the inward flow of the collapsing vapor plume will be incorporated into the cloud. Some regions of the bow shock are hot enough to melt nebular dust and form melt droplets derived from nebular materials.

Thermal evolution of the warm, dense cloud: The collapsed vapor plume is a thermal and dynamical disturbance in the nebula. The supersonic vapor plume expansion and collapse overprint the pre-impact gas motion associated with turbulence in the nebula. The bow shock continues to propagate outward and decays into a sonic disturbance. The bulk density of the warm cloud, which is laden with dynamically coupled condensates, is larger than the surrounding cold nebular gas. As a result, the warm cloud is stable against convective mixing with the cold nebula. We expect that the interior of the cloud is turbulent and simplify our analysis by assuming an isothermal cloud.

Using our estimates of particle sizes and concentrations, we find that the optical depth of the warm cloud is small compared with the overall size of the feature and the cloud will cool by radiation from a thin photosphere. As the cloud cools, the gas density in the outer layers increases and the cloud contracts. To maintain pressure equilibrium, the surrounding solar nebula responds to the contraction by flowing inwards.

We estimated the order of magnitude for the inward flow velocities for isothermal spherical clouds. We find that the convergent flow velocity can exceed the gravitational escape velocities of the densest clumps. We propose that thermal contraction of the cloud is a significant process that aids concentration of condensed material and may shorten the gravitational collapse time of the dense clumps in the cloud.

Timescales for formation of new planetesimals: The self-gravitational collapse time is of order $1/\sqrt{G\rho}$, where G is the gravitational constant and ρ is the bulk density of the condensates. Based on geochemical and isotopic constraints on the chondrule formation region [9,10], the concentration of chondrules corresponds to bulk densities of order 0.01 to 0.001 kg m^{-3}, and the gravitational collapse timescales are weeks.

We estimate that collapsed vapor plumes from collisions between 100-km scale planetesimals take several days to several weeks to radiatively cool to the temperatures of the background nebula. If the convergent flow of the nebula is maintained over this time period, then new planetesimals may form in the densest regions of the cloud.

Ultimately, we expect the efficiency of new planetesimal formation to vary substantially with each impact event. Different impact parameters lead to more dispersed or more clumped vapor plumes. In cases where the cooling timescales are longer, the cloud may be broken up by background turbulence before cooling is complete.

Because the cloud is heterogeneous, we expect multiple new planetesimals, of varying sizes, to form in close proximity. Future work will examine the late time evolution of the dust, droplets, and new planetesimals in the cloud. Some material may continue to accrete onto planetesimals large enough to resist nebular gas drag. A portion of the cloud materials will be dispersed as small particles whose orbits evolve quickly under gas drag.

Conclusions: At this meeting, we have identified and investigated several new processes that occur during vaporizing collisions between planetesimals in the presence of nebular gas [4-8]. These processes lead to collision outcomes that are substantially different than collisions in empty space [11]. Analytic expressions to approximate impact outcomes must be re-evaluated for collisions in the nebular gas.

Here, we have identified previously unrecognized processes that are relevant to planetesimal formation: (i) concentration of small particles coupled to hydrodynamically collapsing vapor plumes and (ii) convergent gas flow driven by radiative cooling of the collapsed vapor plume. Based on order of magnitude estimates of the dynamical and thermal evolution of the vapor plume, we argue that new planetesimal formation is likely to occur in the warm, dense cloud created by vaporizing planetesimal collisions.

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