SHOCK WAVE MODELS: DEPENDENCE OF THERMAL HISTORY AND TYPE II CHONDRULE COMPOSITION ON WATER AND DUST ENRICHMENT. A. V. Fedkin[1], F. J. Ciesla[2] and L. Grossman[1,3], [1]Dept. of Geophysical Sciences, Univ. of Chicago, Chicago, IL 60637(avf@uchicago.edu), [2]Dept. of Terrestrial Magnetism, Carnegie Inst. of Washington, Washington, DC 20015, [3]Enrico Fermi Inst., Univ. of Chicago.

Introduction: Models for formation of chondrules in nebular shock waves [1-3] have investigated the effects of gas pressure, shock velocity and concentration of chondrule precursors (*i.e.*, dust enrichment) on the P-T-time history. A kinetic model for evaporation and recondensation of chondritic matter, based on metal-silicate, liquid-crystal phase relations of [4] was developed in [5]. Using the P-T-time history of a gas+solid system of solar composition subjected to a 7 km/sec shock wave from [2], Fedkin *et al.* [5] were able to reproduce the mineralogical and chemical composition, the olivine composition histogram, the FeO content of the glass, and the small Mg, Si and Fe isotopic fractionations typical of Type II porphyritic olivine chondrules, by assuming that a starting material formed at $\log f_{O_2} = IW - 2.6$ was shock-processed in a system enriched in dust by a factor of 300 and in water by a factor of 550 relative to solar composition. Because the dust and water enhancements necessary to explain the composition and oxidation state of Type II chondrules are so large, however, it is likely that the P-T-time history of such a system subjected to a 7 km/sec shock wave will be quite different from that computed for solar composition in [2] and [5]. Here, we explore the effects of gas pressure, shock velocity, dust enrichment and water enrichment on both the thermal history and chemical evolution of matter processed in nebular shock waves, using the model of [6] which specifically accounts for the presence of water (but not radiative losses due to line cooling) in the energetics of the shocked system.

Effects on Thermal History: Thermal histories of nebular gas+dust systems computed for various values of shock velocity and dust enrichment are shown in Fig. 1, where time zero is the point when T first rises above 1400K. All cases shown assume a chondrule diameter of 1.0 mm, a water enrichment of 550x solar, and a starting total pressure, P^{tot}, of 10^{-6} bar at 300K. Post-shock gas temperatures and pressures increase with shock velocity. Upon crossing the shock front, chondrules experience a higher frequency of collision with gas molecules when the starting total pressure, P^{tot}, and the pre-shock T are higher. Collisions with water molecules are more energetic than with lower-mass molecules. Chondrules heat both the gas behind the shock front and one another more efficiently when they are more concentrated. Thus, chondrules reach higher peak temperatures (T_{max}) at higher P^{tot}, shock velocity, water abundance and dust enrichment (and thus chondrule abundance) than would otherwise be the case. The mass density of hot, post-shock gas increases with increasing P^{tot} and water abundance, requiring more energy to be lost from the system in order to cool by a given amount, resulting in slower cooling rates of chondrules after they come to rest with respect to the gas than would otherwise be the case. The exact rate at which the chondrules cool is largely determined by the abundance of chondrules in the shock. As found in previous work [2,3], chondrules cool when they radiate away their energy as they pass through the shocked gas and are no longer exposed to the radiation coming from the hottest chondrules immediately behind the shock front. As chondrule enrichment rises, the optical depth between the chondrules and the shock front rises more rapidly, leading to this radiation being blocked more quickly, resulting in faster cooling rates. Higher shock velocities produce higher spatial concentrations of chondrules behind the shock, also resulting in faster cooling. The declines in both T_{max} and post-shock cooling rate with falling dust enrichment at constant shock velocity are clearly seen in Fig. 1, as is the effect of shock velocity on T_{max}. The effect of water and dust enrichment is dramatic: for a system of solar composition shocked at 7 km/sec at the same P^{tot} as in Fig. 1, T_{max} is only 922K. For a given mass of chondrules, number abundance rises with falling chondrule size, leading to a more rapid increase in optical depth behind the shock. Thus, a population of larger chondrules would cool more slowly than a population of small ones.

Effects on Composition: As in [5], the present calculations assume a volatile-free, initially reduced chondritic precursor (containing 28 wt% Fe and 2.3 wt% FeO) immersed in a gas enriched in water by a factor of 550 relative to solar composition, and include simple models of non-equilibrium melting, fractional crystallization of olivine, oxidation rate of metallic nickel-iron and its partial physical separation from the silicate-rich chondrule during cooling. In the present work, the ambient pressure is augmented by the computed ram pressure for the first time.

For a 7 km/sec shock in a system enriched in dust by a factor of 900, pre-shock temperatures are so high for so long that all FeO evaporates prior to the beginning of the temperature spike, and the precursor composition evolves into the system CMAS + metallic Fe.

For a 7 km/sec shock and dust enrichment of 600x, T_{max} (2102K) exceeds the liquidus (1957K), and extensive evaporation occurs. At the same shock velocity but only 300x dust enrichment, T_{max}=2004K. In both cases, olivine does not reappear until after substantial cooling, during which time the high dust enrichment causes a large fraction of the evaporated iron to recondense (Fig. 2). As a result, the maximum δ^{56}Fe preserved by any olivine in the 300x case is 2.9‰ and the bulk chondrule has δ^{56}Fe of ~1.3‰. In both cases, most olivine lies between Fa_{14} and Fa_{19}, and the composition histograms have low tails extending beyond Fa_{60} (Fig. 3). Even a slight amount of subcooling of objects subjected to these thermal histories would form Type II barred olivine chondrules with very small δ^{56}Fe. Because of fractional crystallization of very fayalitic olivine late in the cooling history, the FeO content of the silicate liquid declines with falling T. In order to reproduce the wt% FeO commonly observed in mesostases of Type II chondrules, the liquid must be quenched when its FeO content lies between 5 and 10 wt%. In the cases presented here, however, cooling rates are too fast to allow >80% of the K to recondense into the silicate liquid before the FeO content of the liquid falls below this range, yielding an object undepleted in K, as in Type II chondrules, only if the FeO content of the liquid is lower than observed.

When the shock velocity is 6 km/sec and the dust enrichment is 600x, pre-shock, peak and post-shock temperatures are all relatively low, 33 wt% of the silicate fraction is unmelted olivine at T_{max} (1847K) and relatively little evaporation of Mg (<1%), Si (<1%) or Fe (16%) occurs. Most olivine is Fa_{11}-Fa_{24}, and its composition histogram has a low tail extending beyond Fa_{60}. For a shock velocity of 6 km/sec and a dust enrichment of 300x, T_{max} is only 1742K, 50 wt% of the silicate fraction is unmelted olivine at T_{max} and <5% of the iron evaporates. Most olivine is Fa_{20}-Fa_{23}, and the bulk δ^{56}Fe of the chondrule is 0.02‰. In both cases, the dust enrichment is still too low to allow >80% K recondensation into the chondrule melt before its FeO content falls below 5 wt%. At that point for the 600x case, the bulk chondrule has δ^{25}Mg=0.0, δ^{29}Si=0.02, δ^{56}Fe=0.27 but δ^{41}K=-7.4‰. Except for the K isotopic compositions, the final products in these thermal histories would resemble Type II porphyritic olivine chondrules. In these calculations, the sluggish recondensation rates of Na and K may be due to poor estimates of their high-temperature evaporation coefficients.

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