ADIABATIC SHOCK WAVES IN ICY REGIONS OF THE SOLAR NEBULA: IMPLICATIONS FOR ORIGINS OF PHYLLOSILICATE MINERALS IN PRIMITIVE METEORITES.

F. J. Ciesla[1], D. S. Lauretta[1], B. A. Cohen[2], and L. L. Hood[1], [1]*Department of Planetary Sciences/Lunar and Planetar Laboratory, University of Arizona, Tucson AZ 85721 (fciesla@lpl.arizona.edu),* [2]*Hawaii Institute of Geophysics & Planetology, University of Hawaii at Manoa, Honolulu HI 96822.*

Introduction: Phyllosilicate minerals are present in many primitive meteorite classes including CI, CM, and CV carbonaceous chondrites and type-3 ordinary chondrites [1-4]. Their origin has been a scientific puzzle for many years. Thermochemical equilibrium calculations show that serpentine, a phyllosilicate mineral that is abundant in the CM chondrites, is stable below 225 K in the canonical solar nebula [5]. However, kinetic considerations suggest that the rate of serpentine formation is too slow to occur within the lifetime of the solar nebula under these conditions [5]. Because of this kinetic consideration, it has long been accepted that serpentine and other phyllosilicate minerals, particularly those found in chondrule rims, formed during aqueous alteration on a small body in the early solar system.

Petrologic studies of the CM chondrites show that phyllosilicate minerals occur as fine-grained rims around chondrules and other coarse-grained components [2,6]. The rims have many features that suggest formation by accretion of fine-grained minerals. This association between chondrules and fine-grained rims is inconsistent with in situ phyllosilicate formation on the CM chondrite parent asteroid. To resolve this problem, a complex history for the origin of fine-grained phyllosilicate minerals has been proposed [2]. Since serpentine formation is inhibited in the solar nebula, aqueous processes on a precursor parent body have been invoked. This body was then disrupted by a catastrophic impact, dispersing the fine-grained material back into free space. Chondrules and other coarse-grained minerals then encountered this dust, accreted their fine-grained rims, and then became incorporated into the final parent body.

In this study we present an alternative formation mechanism for fine-grained phyllosilicate-rich chondrule rims. We investigate the environmental conditions that result from an adiabatic shock wave in an icy region of the solar nebula. Such a mechanism is a leading candidate for chondrule formation [7].

Shock Model: The thermal evolution of silicates encountering a shock wave in the solar nebula has been studied by many authors to explain the rapid heating required to form chondrules [8-11]. We have modified the model of [10] to study the evolution of solids made of water ice and to model the rate of vaporization of the ice. The rates of sublimation and condensation are taken from [12], and evaporative cooling is considered as in [13].

We present the results for the case of a nebula initially at 10^{-5} atm and 150 K (slightly below the condensation point of water ice). We assume that the nebula gas is composed of H_2 and H_2O with water ice uniformly suspended throughout at a solar composition density, such that the water vapor pressure is in equilibrium with the ice. The ice particles are assumed to initially be 1 mm spheres. The shock velocity is chosen as 8.8 km/s because this is what we find to be the minimum required to completely melt silicates to form chondrules in a nebula of similar structure.

Figure 1 shows the vapor pressure of water with distance behind the shock. The P_{H_2O} reaches a maximum of 5.5×10^{-7} bars at a distance of 10 km behind the shock, which is the point at which the ice particles completely sublime. This takes place 1.3 seconds after passing through the shock. The gas reaches a maximum temperature of 2754 K. The gas cools through dissociation and molecular vibrations, but the pressure remains constant during this process. Thus, the water vapor pressure also remains constant until condesation begins (while we ignore the effects of water dissociation, which would be important at the high temperatures, most of the water would have reformed once the system began to cool down to the temperatures at which phyllosilicates are stable).

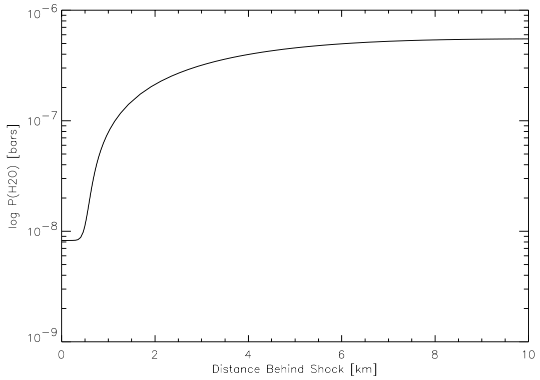

Figure 1: Water vapor pressure as a function of distance behind the shock front described in the text.

Hydration Model: Using the conditions set up by the shock model, we investigate the hydration of forsterite using the Simple Collision Theory (SCT) described in [14]. This theory was used in [5] to show that the reaction $2Mg_2SiO_4 + 2H_2O(g) = Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$ is kinetically inhibitted in the canonical solar nebula. We recalculated the timescales for forsterite hydration to form serpentine and brucite using the post-shock values in our shock model.

The temperature of stability for serpentine is higher (260 K) than that considered in [5] because of the higher P_{H_2O}. We consider the hydration of four different silicate grain radii: 0.1 μm, 1μm, 10μm, and 100μm. Using the numbers given in [6], we have calculated the chemical lifetime for hydration for each forsterite grain size and plot them in Figure 2 as a function of temperature. At the stability temperature of serpentine, it would still take an amount of time greater than the lifetime of the solar nebula for the phyllosilicates to form.

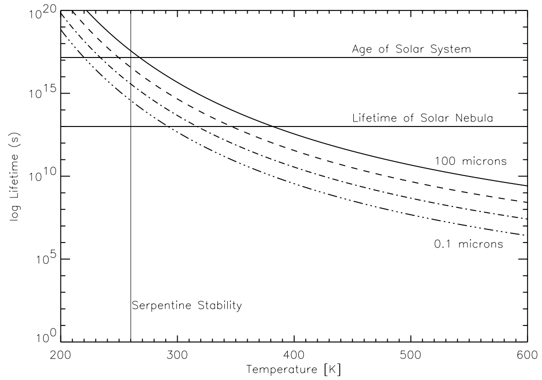

Figure 2: Chemical and physical lifetimes associated with the hydration of forsterite grains by water vapor to form serpentine in the solar nebula (after [5]).

However, it was pointed out by [15] that the activation energy used by [5] may have been too high. The chemical lifetime for a reaction is proportional to exp(E_a/RT). In [5] E_a was set equal to 70 kJ/mol, while based on the work of [16], it was suggested by [15] that E_a is closer to 32.5 kJ/mole. At a temperature of 260 K, this leads to a decrease in chemical lifetime by over 7 orders of magnitude. Figure 3 shows the same calculations as Figure 2, except an activation energy of 32.5 kJ/mole is used. At this activation energy, the chemical lifetime for hydration of a 0.1 μm forsterite grain is approximately one year, and for the other sizes considered, the time is still much less than the lifetime of the nebula.

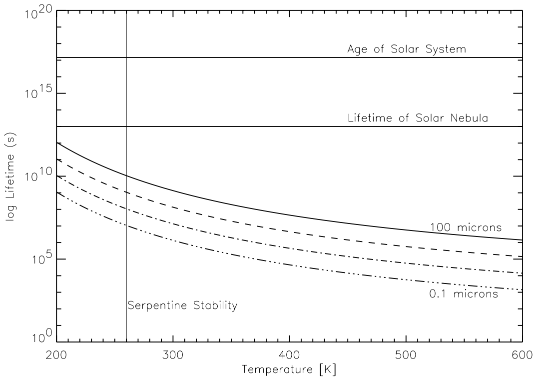

Figure 3: Similar to Figure 2, except that a lower activation energy is used for the reaction studied.

Therefore, in our model, the hydration of silicate grains in the solar nebula may not have been as kinetically inhibited as once thought. However, whether chondrule fine-grained rims were created by this process depends on other factors as well, including the lifetime of the enhanced P_{H_2O} and the radial location of the chondrule-forming region, which we will investigate further.

References: [1] Tomeoka and Buseck 1990, *GCA* **54** 1745-1754. [2] Metzler et al. 1992, *GCA* **56** 2873-2897. [3] Keller et al. 1990, *GCA* **54** 2113-2120. [4] Alexander et al. 1989, *E&PSL* **95** 187-207. [5] Prinn and Fegley 1989, in *Origin and Evolution of Planetary and Satellite Atmospheres*, 78-136. [6] Lauretta et al. 2000, *GCA* **64** 3263-3273. [7] Rubin 2000, *Earth-Sci. Rev.* **50** 3-27. [8] Hood and Horanyi 1991, *Icarus* **93** 259-269. [9] Hood and Horanyi 1993, *Icarus* **106** 179-189. [10] Ciesla & Hood 2001, *LPSC XXXII*. [11] Desch & Connolly 2001, *LPSC XXXII* [12] Sepulver and Lin 2000, *Icarus* **146** 525-540. [13] Moses 1992, *Icarus* **99** 368-383. [14] Fegley 2000, *Space Sci. Rev.* **92** 177-200. [15] Ganguly and Bose 1995, *LPSC XXVI* [16] Wegner and Ernst 1983, *Amer. J. Sci* **283-A** 151-180.