HOW MUCH DUST CAN BE PROCESSED BY A SINGLE LIGHTNING BOLT IN THE SOLAR NEBULA? Joseph A. Nuth III[1] and John. A. Paquette[2], [1]Solar System Exploration Division, Code 690, NASA's Goddard Space Flight Center, Greenbelt MD 20771 (joseph.a.nuth@nasa.gov), [2]Astrochemistry Laboratory, Code 691, NASA's Goddard Space Flight Center, Greenbelt MD 20771.

Introduction: We have created a model of nebular lightning to explain the fractionation of oxygen isotopes in the solar system along a line of unit slope rather than the 0.52 equilibrium fractionation line[1]. The model produces the observed fractionation through processing of nebular dust by repeated lightning bolts over the last five million years of nebular accretion. While the average oxygen isotopic composition of nebular dust becomes more ^{16}O-depleted with time, the slope 1 line is produced by remnant materials that are "left behind" either as grains or components too large to be evaporated easily or as materials that stochastically escape further processing. In general terms, our model predicts that materials rich in ^{16}O are often older than grains that are more depleted in ^{16}O.

We note in passing that although the Photochemical Self Shielding (PSS) model originally produces a slope 1 line in O isotopes during the photodissociation step, subsequent reactions with nebular hydrogen to produce water and reactions of water with silicates should convolve that line with the familiar slope 0.52 fractionation lines to produce a slope less than 1 for the overall process as proposed [2 – 4]. We suggest that any fractionation resulting from PSS is based on the same time dependent average increase in ^{16}O-depleted dust found in the lightning model with remnant grains or components tracing out the past history of the dust.

The lightning model depends on a number of parameters, and in this study we quantify the effects of variations in two of the most important: the dust evaporation coefficient and the assumed temperature of the lightning bolt. We show that the effect of varying the evaporation coefficient by two orders of magnitude is much less than the effect of a four-fold increase in the lightning bolt temperature, indicating that the composition of the grains heated by the lightning bolt is much less important than is the temperature of the bolt itself when computing the quantity of material vaporized by each lightning stroke.

Model of Nebular Lightning: The model [1] assumes that a constant fraction (~5%) of the accretion energy of the nebula is dissipated as lightning. Since the accretion energy is assumed to decrease exponentially with time, so too does the energy dissipated as lightning. Based on previous work on nebular lightning [5-7] a lightning bolt was assumed to be a cylinder 100 km long and ten electron mean free paths (about 7 m) in radius (See Figure 1). Given these parameters the energy in a single lightning bolt can be calculated and based on the available energy, the relative sizes of a bolt and the volume of the inner nebula (treated as a disk 5 A.U. in radius and 1 A.U. thick) the interval between lightning strokes per unit volume in the inner nebula can be calculated. The interval between successive lightning bolts is initially about 5450 years. Of course, as the energy available for lightning decreases, this interval will monotonically increase as the rate of lightning tapers off.

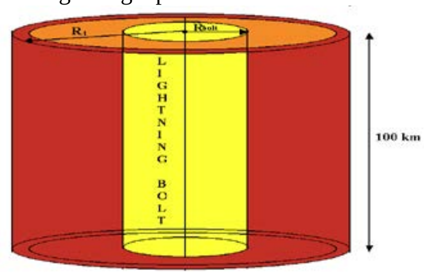

Fig. 1: The model assumes that a lightning bolt fills a cylinder 100 km long with a radius of R_{bolt} = 10 electron mean free paths, or about 7 m in nebular conditions. The region around the lightning bolt is modeled as a series of concentric cylinders, with the ith such cylinder having a characteristic radius R_i. The outermost cylinder is 840 m in radius.

The initial dust distribution is assumed to be that given for the interstellar grain population [8] and the dust is assumed to consist entirely of SiO. Recent work indicates that SiO is a good candidate to initiate dust nucleation [9]. The dust coagulates for 5450 years before the first lightning bolt, so the initial size distribution of nebular dust is considerably larger than the interstellar grain size distribution. During the stroke (assumed to last for 30 ms) the temperature is instantly increased to a high (5000K – 20,000K) value and the dust inside the bolt is completely evaporated. After the lightning bolt the temperature decreases for several hours due to a model imposed cooling rate. Both vapor and heat are allowed to diffuse radially, and a large region around the ionization channel is heated, evaporating existing grains either completely or partially. As the temperature drops, new grains nucleate and grow. Grains that were not completely evaporated can also grow as SiO condenses on their surfaces. The dust affected by the lightning bolt is assumed to be slightly depleted in ^{16}O based on the results of Kimura, et al., [10]. Recent results of Chakraborty et al. [11] also suggest that the oxygen isotopic composition of condensates becomes more ^{16}O-depleted following condensation in a hydrogen-rich, laser-evaporated ion plume.

After cooling, coagulation and mixing of the radially diverse grain size distributions proceed. Coagulation continues for another 5400 years, essentially bringing the grain radius distributions to the state that they would occupy immediately prior to the next lightning bolt. A series of such bolts produces a change in the oxygen isotopic composition of the processed solids that is initially rapid, but that slows as lightning becomes less frequent.

Model Results: Figure 2 shows the final grain radius distributions calculated assuming a 5000 K lightning temperature. The grains range in size from ~1 micron to ~13 microns, peaking near 7 microns and are comparable to grains in the matrices of primitive meteorites. The different evaporation coefficients have little effect on the ultimate grain radius distributions. It is possible that small increases in grain size would be expected as a result of repeated lightning processing and subsequent intervals of coagulation.

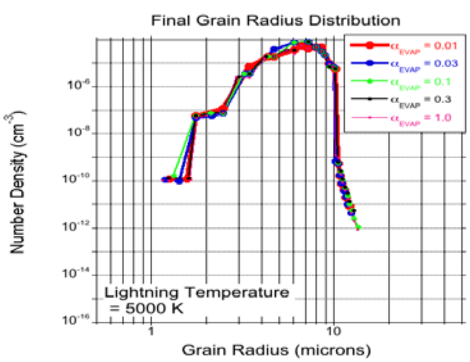

Fig. 2 The final grain radius distribution for a lightning bolt of 5000 K. Five different point sizes correspond to five logarithmically spaced evaporation coefficients. Curves corresponding to different evaporation coefficients are similar. Grains range in size from ~1 micron to ~13 microns. The distribution peaks just above 7 microns.

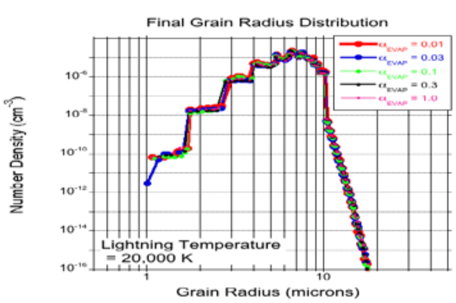

Fig. 3: The final grain radius distribution for a 20,000 K bolt. Grains range in size from ~1 to ~19 microns and peak just below 7 microns.

Figure 3 shows final grain radius distributions assuming a 20,000 K bolt for the same five evaporation coefficients. Grains range from ~1 micron to ~19 microns, peaking again at ~7 microns, just as before. The average peak number density has decreased to 2.1 x 10^5 per cubic centimeter. Different evaporation coefficients have little effect on the grain radius distributions and it would appear that neither varying the lightning temperature nor the evaporation coefficient has much effect on the final grain size distributions. The largest grains are obtained with the highest lightning temperature, but the peak grain radius is essentially unchanged. The peak number density drops as the temperature increases due to mass conservation as higher temperatures produce larger grains, so the number density of smaller grains decreases.

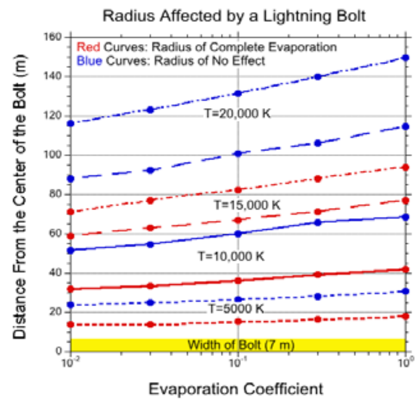

Fig. 4: Red curves show radii of complete evaporation. Blue curves show radii of no effect for 4 different lightning temperatures plotted versus evaporation coefficient. Dotted lines are for 5000 K, solid lines for 10,000 K, dashed lines for 15,000 K, and dash-dotted lines for 20,000 K bolts.

Figure 4 demonstrates that variation in the temperature of the ionization channel does have a significant effect on the quantity of dust processed in each lightning bolt. Red curves denote the radius of total evaporation; within that radius all dust is completely destroyed. Blue curves indicate the radius beyond which the lightning bolt had no effect, even on the smallest grains. Curves are plotted versus evaporation coefficient for four lightning temperatures. An increase with increasing evaporation coefficient is obvious and is also small. Increasing the evaporation coefficient by two orders of magnitude has roughly a 30% effect on the radius away from the ionization channel affected by a lightning bolt. A much larger effect is caused by a change in the temperature of the ionization channel. The increase in the evaporation radius affected is more than linear. Due to the assumption of cylindrical symmetry in this model, the volume processed by each lightning stroke depends on the square of the evaporation radius.

References: [1] Nuth J.A., Paquette J.A., & Farquhar A. 2012.*MAPS* 47:2056–2069.[2] Yurimoto H. & Kuramoto K. 2004.*Science* 305:1763–1766.[3] Lyons J.R. & Young E.D. 2005.*Nature* 435:317–320.[4] Clayton R.N. 2002. *Nature* 415:860–861.[5] Love, S.G., Keil K., & Scott E.R.D., 1995.*Icarus* 115:97-108.[6] Gibbard, S.G., Levy E.H., & Morfill G.E., 1997.*Icarus* 130:517-533.[7] Desch S.J. & Cuzzi J.N. 2000. *Icarus* 143:87–105.[8] Mathis, J.S., Rumpl, W., Nordsieck, K.H., 1977. *Ap.J.* 217:425–433.[9] Paquette, J.A., Nuth, J.A. & Ferguson, F.T. 2011, Ap.J. 732 , 62-74. [10] Kimura Y., Nuth, J.A., Chakraborty S., & Thiemens M. 2007.*MAPS*:42:1429–1439.[11]Chakraborty,S., Yanchulova, P. & Thiemens, M.H., 2013,Science, 342, 463–466.