PROTOSTARS ARE NATURE'S CHEMICAL FACTORIES. Joseph A. Nuth III[1] and Natasha M. Johnson[1,2], [1]Astrochemistry Laboratory, Solar System Exploration Division, Code 691 NASA's Goddard Space Flight Center Greenbelt, MD 20771 (nuth@gsfc.nasa.gov) [2]NAS/NRC Resident Research Associate

Introduction: $H_{2\ 2}$ and CO are the most abundant molecular constituents in astrophysical environments, including protostellar nebulae. Although some organic molecules may be produced on very long timescales by the irradiation of ices formed on the cold surfaces of interstellar grains [1,2] and these molecules may be an important source of raw materials leading to the origin of life on Earth, pre-solar organics could be swamped by the efficient conversion of nebular H_2, N_2 and CO to simple organic materials.

We once believed that the conversion of H_2, N_2 and CO to organic materials required the action of a metallic iron catalyst and that these small iron particles would be easily poisoned by nebular sulfur. In addition, much of the iron in the solar nebula is found in silicate and sulfide minerals, neither of which is a good catalyst for the Fischer-Tropsch [$3H_2 + CO \Rightarrow CH_4 + H_2O$] or Haber-Bosch [$3H_2 + N_2 \Rightarrow 2NH_3$] reactions. Our error was in the application of man-made processes to nature. Both the Fischer-Tropsch and Haber-Bosch reactions are specifically engineered to efficiently produce methane or ammonia from the available CO or N_2, respectively. All available studies of these reactions have been carried out in order to increase the efficiency of these processes and to increase the yield of the desired products.

Application of Fischer-Tropsch reaction kinetics to the formation of simple organic materials in the solar nebula [3] demonstrated that it was possible to produce sufficient organic material as gas and dust spiraled in to the protosun to account for the mass of organic matter found in primitive meteorites. Unfortunately, no allowance was made for the loss of these products to the sun, and no good mechanism was proposed for their incorporation into the meteorites.

New Developments: There have been two new developments that could change our view of the production of organic materials in protostellar nebulae. First, studies of the conversion of H_2, N_2 and CO to more complex organic materials have demonstrated that a wide range of materials can provide effective surfaces to promote such reactions [4]. Second, a new model of nebular dynamics that explicitly follows the motions of specific parcels of gas and dust now shows that although the bulk flow of material in the nebula is toward the protosun, some material definitely moves outward as well [5]. Taken together, these new developments can provide considerable insight into the formation of organic materials in protostellar systems.

Nebular Dynamics: Chemistry is a very path-dependent phenomenon, provided that chemical equilibrium is not achieved. Under most non-LTE situations, the final chemistry of the system will depend on what existed initially, how long the reaction was allowed to proceed and the temperature and pressure of the system. Reactions proceed faster at higher temperatures and higher pressures such as those found in the innermost regions of protostellar nebulae. Yet such ideal reaction conditions cannot provide complex organic compounds to meteorite parent bodies or to nascent comets unless the products of such reactions can be transported to the sites where primitive bodies begin to form. In the case of comets that finish growing at 5 to 10 A.U. aggregation may begin as far as 100 A.U. from the protosun in a minimum mass nebula [6]. For more massive nebulae the aggregation process would begin closer to the sun and the drift that occurs during growth would be reduced, yet transport to several 10s of A.U. would still be required to incorporate the products of high temperature, high pressure reactions throughout the body [7,8]. Boss [5] has demonstrated that nebular materials can be transported out to well beyond 20 A.U.

Surface-Mediated Chemistry: In chemical engineering applications it is essential to maintain the catalyst in pristine condition to ensure the continued production of a pure product stream. Catalyst poisoning can result in the production of unwanted product or in the effective loss of the catalytic surface that promotes the reaction of interest. If we view the conversion of H_2, N_2 and CO to nebular organics as a catalytic process, then it will always fall short of expectations. First, we have previously demonstrated that amorphous iron silicates provide reasonably good surfaces to promote the reaction of H_2, N_2 and CO to organic materials resembling those found in meteorites [9]. Second, we have also demonstrated that although they are not as efficient, amorphous magnesium silicates, bronzite and a range of other natural materials also promote the formation of organic materials from H_2 and CO. One can infer from these studies that almost any surface will promote the conversion of H_2 and CO to organic materials of some type, though the efficiency and the products of the reaction may depend on the specifics of the system. Furthermore, although reaction of H_2 and CO on these surfaces does produce volatile organic products, a major reaction product appears to be a macromolecular organic coating on the surfaces of the grains.

We have been carrying out studies of the surface-mediated reaction of H_2, N_2 and CO on grain surfaces for several years and a number of interesting facts are beginning to emerge beyond those that we had initially intended to measure. First, as noted above, many surfaces promote the conversion of H_2, N_2 and CO into organic materials beyond just iron or amorphous iron-containing silicates. Second, although we know that the reaction of H_2, N_2 and CO results in the formation of a macromolecular coating on our grains, we do not notice a significant decrease in our reaction rate even when this coating comprises up to 10% by mass of the grains [9]. Finally, although some grain materials, such as amorphous magnesium silicates, initially do not act to break the very strong molecular nitrogen bond (we initially see no nitrogen containing products in our circulating gas) later experiments using that same grain type eventually do begin to show evidence for nitrogen-containing products. This appears to imply that the organic coating formed as one of the products of the reaction of H_2, N_2 and CO on any grain surface also acts as an effective surface for the conversion of H_2, N_2 and CO into organic materials.

Take it to the Extreme: We have shown that many materials are capable of converting H_2, N_2 and CO into a macromolecular organic coating on the original grain surface and that this surface is, itself, capable of promoting the reaction of H_2, N_2 and CO into organic materials. Kress and Tielens [3] demonstrated that simple Fischer-Tropsch reactions on tiny grains of iron were capable of producing sufficient organic material to account for that observed in meteorites, albeit without accounting for the potential inefficiency inherent in incorporating such materials into the parent bodies. If every dust grain entering a protostellar nebula is capable of acquiring a coating that promotes the conversion of H_2, N_2 and CO into organic molecules then this will greatly increase the production of organics even in a system where all such production must occur as the dust and gas migrates in towards the protostar. However we also know that the rate of conversion of H_2, N_2 and CO into organics increases with both temperature and pressure, and will therefore be most efficient in the hotter, denser inner nebula. Boss [5] has shown that the products from such reactions could easily migrate outwards to become incorporated into the meteorite parent bodies or into comets. In fact, until the formation of the giant planets begins to open significant nebular gaps at the midplane, there is no limit to the distance that such materials could migrate. Even after the opening of such gaps, it might still be possible for material to travel outward both above and below the nebular midplane.

Conclusion: Dust grains falling into a protostellar system can provide surfaces that promote the reaction of H_2, N_2 and CO into both volatile organics and a macromolecular coating that continues to promote the formation of organic materials. Although the reaction is most efficient in the innermost regions of the nebula this does not pose significant problems as the reaction products as well as the coated grains can migrate back out to the far reaches of the nebula, thus seeding the entire nebula with the organic building blocks of life. All that would then be needed are appropriately pleasant conditions allowing such seeds to germinate.

References:

[1] Gerakines, P. A., Moore, M. H., and Hudson, R. L. (2004) *Icarus* **170**, 202 - 213. [2] Bernstein, M. P., Moore, M. H., Ashbourn, Dworkin, J. P., Elsila, J., Iraci, L., Sandford, S. A., Allamandola, L. J. & Zare, R. N. (2003) *Astrobiology,* **2**, 605; Bernstein, M. P., Dworkin, J. P., Cooper, G. W., Sandford, S. A., Allamandola, L. J. (2002) *International Journal of Astrobiology,* **1**,147 [3] Kress, M. E. and Tielens, A. G. G. M. (2001) *MAPS,* 36, 75 – 91. [4] Hill H. G. M. and J. A. Nuth (2003) *Astrobiology* 3, 291 – 304. [5] Boss, A. P. (2004) *Ap.J.* 616, 1265 – 1277. [6] Weidenschilling, S. J. (1997) *Icarus* 127, 290. [7] Nuth, J. A., Hill, H. G. M. and Kletetschka, G. (2000) *Nature* 406, 275 - 276. [8] Hill, H. G. M., Grady, C. A., Nuth, J. A., Hallenbeck S. L. and Sitko, M. L. (2001) *Proc. Natl. Acad. Sci.* 98, 2182-2187. [9 Hill, H. G. M., Pearson, V. K., Sephton, M. A., Nuth, J. A. and Gilmour, I. (2002) *LPS XXXIII* #1311.