SOLAR NEBULA CONDENSATES AND THE COMPOSITION OF COMETS;

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A wealth of gaseous and condensed compounds have been identified in data from the Giotto and Vega flybys of Halley's comet, and from complementary ground-based studies of Halley and other recent comets. The interpretations in terms of cometary origin have been characterized by a high degree of selectivity of data in order to fit simple (and largely preconceived) models of particular astrophysical environments in which it is assumed comets formed. In fact, if comets reveal anything about the origin of the solar system, it is that material which eventually went to form the planets passed through a number of stages of chemical and physical evolution in a range of environments from the interstellar medium through hot dense clouds in star-forming regions to the solar nebula. The degree to which the most refractory materials in comets were chemically processed and altered in these environments must of necessity be vastly different from that of the most volatile gases, such as methane and carbon monoxide. More precisely, grains containing silicate and heavy organic components may have been little affected by passage into the solar nebula and subsequent accretion processes, provided they remained on orbits far from the center of the nebula. On the other hand, molecular species such as methane, carbon monoxide, ammonia and perhaps water ice would have been lost from the grains at various stages in molecular clouds and during entry into the nebula. These species in Halley's comet may reflect the final stages of cometary accretion in the outer part of the solar nebula.

This talk focusses on interpretation of the volatile abundances in Halley's comet in terms of models for chemical and physical processes in the solar nebula. Key ratios of the oxidized and reduced species of nitrogen and carbon are identified which tell something of the chemical history of the environment in which cometary grains accreted to form the nucleus. Isotopic abundances are also applied to this problem. I will show that the abundances of methane and carbon monoxide are consistent both with models of solar nebula chemistry and chemical processing on grains in star-forming regions. Ultimately, limitations of the current data set on molecular abundances in comets and star-forming regions prevent a definitive choice between the two.

Processes important to the composition of outer solar system bodies are:

Gas phase chemistry in the solar nebula: The models of Lewis and Prinn and Fegley (see Prinn and Fegley, 1989) for kinetic inhibition of homogeneous gas-phase, and heterogeneous grain-gas, reactions lead to the following conclusions: (a) the inner poriton of the solar nebula (where reactions take place) is dominated by carbon monoxide and molecular nitrogen as the primary carbon- and nitrogen-bearing molecules. Carbon dioxide, methane and ammonia are minor constituents. Most of the elemental oxygen is bound up as carbon monoxide; water and silicates sequester the remainder. Possible depletion of water by diffusive redistribution (Stevenson and Lunine, 1988) leads to somewhat higher methane abundances in the inner nebula (Engel et al., 1988). Gas-grain catalysis may be effective only down to ~600 K, where it is poisoned by chemical combination of sulfur with metal grains (Fegley, 1988). In the higher pressure nebulae around giant planets, the results of the MIT group show that methane and ammonia may dominate, with water sequestering nearly the full elemental oxygen abundance.

Imperfect mixing in the solar nebula: Stevenson (1989) showed that radial mixing is severly limited in a viscous accretion disk model of the solar nebula, so that over 90% of the material in the outer solar nebula (>10 AU) has never been exposed to inner nebula chemistry. This dilutes the importance of methane and ammonia manufactured in the inner part of the disk, and suggests that chemical and physical processes in the surrounding molecular cloud and those associated with the molecular cloud-solar nebula interface could play an important role in determining outer solar system abundances. Also, mixing between giant planet sub-nebulae and solar nebula may affect the latter's composition (Prinn and Fegley, 1989).

Condensation: Concerning volatile species, condensation of water occurs in the solar nebula at roughly 150K. Condensation of ammonia hydrates using available ammonia occurs below 100K, and the diagnostic volatiles methane, carbon monoxide and molecular nitrogen condense at significantly lower temperatures (less than 40K). Of the last three only methane, if it is abundant, is predicted to condense in most models of the solar nebula pressure-temperature profile. The other volatiles must be trapped in less volatile condensates, most plausibly clathrated into or adsorbed on water ice. In giant planet sub-nebulae, the condensation temperatures of all species are raised by tens of degrees relative to the solar nebula.

Clathration: Trapping of small non-polar or weakly-polar species in clathrate hydrate is effective provided exposure of the ice to the gas is extensive. Formation of clathrate containing a particular guest molecule (e.g. methane) generally is thermodynamically favored at temperatures well above the condensation point of that particular species. The important exception in the nebula is carbon dioxide, but a significant fraction of that species could be trapped in mixed clathrates. Fractionation affecting the composition of trapped gas is significant in clathrate: methane is most easily incorporated, followed by carbon monoxide, and then argon and nitrogen. Objects formed in a solar nebula rich in carbon monoxide may still sequester quantities of methane significant in terms of surface composition.

Adsorption: Where clathrate formation is thermodynamically prevented or kinetically inhibited, physical adsorption of species onto water ice becomes an important trapping mechanism. Apparently amorphous ice has a much higher specific adsorption area than crystalline ice, approaching the carrying capacity of clathrate. Chemical fractionation effects in adsorption should be similar to that of clathration, but hard to predict because the distribution of void sizes in amorphous ice is very poorly known. There is some experimental evidence for low-temperature fractionation (Bar-Nun, 1988).

Processing of interstellar material: Pre-formed grains from interstellar clouds may undergo significant chemical processing in the course of entering the solar nebula. Such processing may occur at the nebula accretion shock, or during drag heating associated with infall. Only a modest (tens of degrees) increase in temperature is required to modify the most volatile components carried into the nebula by small grains.

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