THE VITAL ROLES OF WATER AND ORGANICS IN THE EARLY SOLAR SYSTEM. C.M.O'D. Alexander. DTM, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington DC 20015, USA (alexander@dtm.ciw.edu).

Introduction: The importance of water in the evolution of the Solar System cannot be over emphasized. Transport of ice from the outer Solar System may have modified the chemistry and O isotopic composition of the inner Solar System [1-3]. Water had a profound effect on the evolution of most chondrite parent bodies [4]. The water and organics in chondrites are the likely sources of the Earth's water, C, N, noble gases, etc. [5], and are potential means of testing the Nice [6] and Grand Tack [7] dynamical models. Here, their roles at all phases in the early Solar System are explored.

Early dust processing: Many features of IDPs, Wild 2 samples and chondrite matrices suggest a genetic relationship between them. One of these are their fine-grained crystalline silicates, characteristic of which is their wide range of Fe contents (e.g., Fa_0 to Fa_{50}). They also have near terrestrial (i.e., non-solar) O isotopic compositions [8, 9]. The crystalline silicates are thought to be condensates that formed in the inner Solar System. The fact that they were distributed so widely in the solar nebula suggests that they formed early in the evolution of the disk.

Assuming that the original interstellar dust had (i) low FeO contents, (ii) solar O isotopes in the (amorphous) silicates and (iii) ^{16}O-poor water-ice, the easiest way to explain the range in Mg# and O isotopes of the crystalline silicates is if they formed in regions with elevated dust/gas and ice/silicate ratios. Objects with greater than solar ^{16}O contents [10] could have formed in the dust depleted regions. Objects (e.g., CAIs, AOAs) with solar oxygen isotopes could have formed in regions where there was no dust/gas fractionation.

In producing the fine-grained dust, to retain roughly solar/CI-like compositions, elements that are incompatible in olivine and low-Ca pyroxene must have condensed in a separate phase(s), the most obvious material being GEMS (Glass with Embedded Metal and Sulfide). Thus, most but not necessarily all GEMS must be solar in origin [11]. GEMS are likely precursors of most of the amorphous material in chondrite matrices.

If water-ice is needed to produce ^{16}O-poor compositions and higher than solar fO_2s, this requires low ambient temperatures and therefore transient heating, which is inconsistent with conditions during the earliest disk-building phase when most material accreted close to the growing Sun. Formation slightly later during FU Orionis outbursts is an attractive alternative as they probably involved vigorous radial transport. Indeed, [12] have suggested that survival of CAIs, the oldest dated solar solids, marked the end of the FU Orionis phase in the early Solar System.

The microstructures of at least some of the fine-grained pyroxene grains require cooling rates that were comparable to those of chondrules, i.e., much shorter than overall FU Orionis timescales. [13] favored chondrule formation, but this seems unlikely as chondrules are elementally fractionated, especially in volatile elements, where as IDPs, Wild 2 and chondrite matrices are closer to solar/CI in their compositions. Also chondrule formation involved high dust enrichments that stabilized silicate/metal melts. There is no evidence that melts were stable during the formation of the grains in IDPs, etc. Rather, their fine-grained nature suggests condensation in low density environments.

Even in ice-rich systems the organic matter would have played a role in determining the fO_2s during heating. If ambient temperatures were above the ice sublimation temperature, concentration of anhydrous dust with CI-like C contents, relative to the gas, will produce the reducing conditions necessary to explain the mineralogies of the enstatite chondrites/achondrites and Mercury [14]. The near-terrestrial O isotopic compositions of the enstatite chondrites/achondrites means that if they formed in this way, it occurred after the phase of dust processing recorded in IDPs, matrix, etc.

Chondrites: When the chondrite parent bodies formed ~2-4 Myr after CAIs, the O isotopic compositions of the water that they accreted was not particularly anomalous [15]. One possible reason for this is that much of the original interstellar water in the nebula had been re-equilibrated when the crystalline silicates and GEMS formed. This reworking of much of the water in the nebula is consistent with the D/H ratios of water in carbonaceous chondrites that are much lower than interstellar water [15]. Nevertheless, the D/H ratios are not solar and, since significant water D enrichments cannot be generated in the nebula [16], the chondrites did accrete some interstellar ices.

Two chondrites groups, the OCs and RCs, have water D/H ratios that are comparable to those of the more enriched comets [15]. However, it seems likely that the enrichments are due to H isotopic fractionation in their parent bodies, e.g., as a result of oxidation of metal by water, as well as H isotopic exchange with [15] and oxidation of [17] D-rich organic matter. These same processes would have affected the CCs, but at least for the CI-CM-CR chondrites their higher water/metal and water/organic ratios mean that the affects on their water D/H would have been less dramatic.

As with water, the organic matter in chondrites probably has both solar and interstellar origins. Material resembling IOM can also be found in IDPs and comets [18]. Large D and ^{15}N enrichments suggest formation of the organics, or their precursors, in cold environments, but whether this was in the ISM or in the outer Solar System remains controversial. One way to distinguish between solar and ISM origins would be to determine the fraction of ISM silicates in GEMS - if all GEMS are solar then all organics must also be solar [19]. However, this too is controversial.

Also debated is whether the range of organic abundances and compositions within and between chondrite groups reflect parent body or nebular processes. That metamorphism would affect organics seems unavoidable, and no O, E, R, CV or CO chondrites have avoided metamorphism. Nevertheless, it does seem at least plausible that all of these groups accreted organic matter that resembled that in CRs [20].

[18, 21] suggested that the variations in organic compositions within and between the CI-CM-CR chondrites are the result of aqueous alteration. Evidence for this comes from both hydrothermal experiments [22, 23] and in variably altered Tagish Lake lithologies [24, 25]. Both the experiments and the Tagish Lake results indicate that the evolution of the IOM is from high D/H and H/C to lower D/H and H/C, i.e., the order of peak alteration temperatures was CR2≈CR1<CM2≈CI1<CM1<CO≈CV. This ordering is somewhat at variance with other estimates of alteration temperatures [4].

Carbonates are ubiquitous in aqueously altered chondrites. Two potential sources of their CO_2 are oxidation of organics by peroxides generated in irradiated ices, or volatiles trapped in the ices. The carbonates are generally enriched in ^{13}C compared to the bulk organics, and also exhibit a considerable range in C and O isotopic compositions. It is possible that there were multiple sources of CO_2 even with a single parent body. However, it seems more likely that the range of isotopic compositions reflect varying temperatures and fluid compositions during carbonate precipitation [26]. The O isotopes would almost certainly have been controlled by water-carbonate fractionation, and the water composition would have evolved as alteration proceeded. The variations in CO_2-carbonate C isotopic fractionation with temperature are too small to explain the range of carbonate compositions. However, CH_4-carbonate and CO-carbonate C isotope fractionations vary considerably with temperature. The range of carbonate C isotopic compositions can be explained by variations in temperature and (CH_4 and/or CO)/CO_2 ratio. Conditions would have been too oxidizing for much CO to be generated in the chondrite parent bodies. Therefore, it would have to have been accreted in the ice, requiring very low ice formation temperatures and contradicting the conclusion that chondritic water formed in the inner Solar System based on D/H ratios. CH_4 is not a major volatile even in cometary ices. Thus if it was a major component in the altering fluids it must have formed in the parent bodies when high H_2 pore pressures were generated by oxidation of metal. Formation of CH_4 is generally kinetically inhibited at low temperatures, but there are minerals in chondrites that can catalyze its formation.

Accretion of Earth's volatiles: In terms of their H and N isotopes, as well as volatile element abundances, the CI and CM like bodies are the most likely the sources of Earth's volatiles [5, 15]. Since the bulk H and N isotopic compositions of CI and CM chondrites probably evolved during their aqueous alteration, the Earth's building blocks cannot have accreted them until after alteration was complete, which was ≥4-5 Myr after CAIs [27] and after Mars-sized embryos had begun to form [28].

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