

Importance of water and organics in the early Solar System: From interstellar inheritance to planet formation. C.M.O'D. Alexander¹, ¹DTM, Carnegie Institution of Washington, 5241 Broad Branch Road, Washington, DC 20015, USA.

Introduction:

The importance of water in the evolution of the Solar System cannot be over emphasized. It would have had an important role in the formation of outer Solar System planetesimals and the giant planets. 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 the carbonaceous (CC), ordinary (OC) and Rumaruti (RC) chondrite parent bodies [4]. The water and organics in chondrites have gained additional significance both as likely sources of the Earth's water, C, N, noble gases, etc. [5], and as potential means of testing the Nice [6] and Grand Tack [7] dynamical models that predict that the parent bodies of the CCs were implanted into the Asteroid Belt from the outer Solar System. Here, the roles water and organics played in the formation of planetesimals and planets are explored.

Early dust processing:

One of the major components of IDPs, comet Wild 2 samples and primitive chondrite matrices are fine-grained crystalline silicates. A characteristic of these silicates in all these materials is a wide range of Fe contents (e.g., Fa₀ to Fa₅₀). They also have near terrestrial (i.e., non-solar) O isotopic compositions [8-10]. 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 in the early growth phase of the nebula. Assuming that the original interstellar dust had low FeO contents, solar O isotopes in the silicates and ¹⁶O-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. However, this requires low ambient temperatures and therefore transient heating, which is inconsistent with conditions during the earliest disk-building phase. Formation slightly later during FU Orionis outbursts is a possibility as if these outbursts are driven by gravitational instabilities radial transport would have been very vigorous. Indeed, [11] have suggested that CAIs mark the end of the FU Orionis phase. However, the microstructures of some pyroxene grains may require cooling rates that are comparable to those experienced by chondrules (i.e., much faster than expected in FU Orionis events). Formation during chondrule formation seems unlikely as chondrules tend to be elementally fractionated, especially in volatile elements, whereas IDPs, Wild 2 and chondrite matrices are much closer to solar/CI in their compositions.

However the crystalline silicates formed, it

seems that the near-terrestrial of silicate dust was established very early, which would be consistent with the recent suggestion that the iron meteorite parent bodies, which have near-terrestrial O isotopes, also formed very early (0.1-0.3 Myr after CAIs) [12].

Chondrites:

When the chondrite parent bodies formed ~2-4 Myr after CAIs [13, 14], the O isotopic compositions of the water that they accreted do not seem to have been particularly anomalous [15]. One possible reason for this is that much of the original interstellar water in the nebula had been re-equilibrated at high temperatures with CO, silicates, etc. This reworking of much of the water in the nebula is consistent with models of disk evolution [16]. It is also consistent with the D/H ratios of water in carbonaceous chondrites that are much lower than interstellar water and most are lower than terrestrial [15]. Nevertheless, the D/H ratios are not solar and, since it appears that significant water H/D enrichments cannot be generated in the nebula [17], this means that chondrites did accrete some interstellar ices. On the other hand, most comets have D/H ratios that are up to 2-3 times the terrestrial ratio. This difference between comets and CCs is one of the reasons that [15] concluded that the carbonaceous chondrites did not form in the outer Solar System.

Two chondrite groups, the OCs and RCs, do 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 [18] 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 effects on water D/H would have been less dramatic.

As with water, the organic matter in chondrites may have solar and/or interstellar origins. Similar material can also be found in IDPs and comets [19]. Large D and ¹⁵N 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 [20]. However, this too is controversial.

Also debated is whether the range of organic abundances and compositions found 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. Unfortunately, it is not possible to extrapolate to unmetamorphosed organic compositions. Nevertheless, it does seem at least plausible that all of these groups accreted organic matter that resembled the organic matter found in CI-CM-CR chondrites [21].

[19, 22] suggested that the variations in organic compositions within and between the CI-CM-CR chondrites are the result of parent body aqueous alteration. Evidence for this has been found in variably altered Tagish Lake lithologies in which the IOM ranges from CR-like in the most primitive lithology to primitive CV-CO-like in the most processed lithology [23, 24]. Hydrothermal experiments have shown that dramatic isotopic and structural changes can take place in IOM heated to ~300°C for only a few days [25, 26]. 300°C is much higher than estimates for alteration of CI-CM-CR chondrites (<100-150°C), but it seems likely that heating for longer times at lower temperatures will produce similar results. The changes in IOM are almost certainly thermally driven. Both the hydrothermal experiments and the Tagish Lake results indicate that the evolution of the IOM is from high D/H and H/C, like CR IOM, to lower D/H and H/C – i.e., the order of peak alteration temperatures was CR₂≈CR₁<CM₂≈CI₁<CM₁<CO≈CV. The ordering is somewhat at variance with other estimates of alteration temperatures [4].

Carbonates are ubiquitous in aqueously altered chondrites. Two potential sources of their CO₂ are oxidation of organics by peroxides generated in irradiated ices, or volatiles trapped in the ices. The carbonates are generally enriched in ¹³C 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 CO₂ 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 [27]. 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 CO₂-carbonate C isotopic fractionation with temperature are too small to explain the range of carbonate compositions. However, CH₄-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 (CH₄ and/or CO)/CO₂ 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. CH₄ 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. Formation of CH₄ 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 [13] and after Mars-sized embryos had begun to form [28].

References:

- [1] Ciesla F.J. and Cuzzi J.N. (2006) *Icarus*, 181, 178-204.
- [2] Yurimoto H. and Kuramoto K. (2004) *Science*, 305, 1763-1766.
- [3] Lyons J.R. and Young E.D. (2005) *Nature*, 435, 317-320.
- [4] Brearley A.J. (2006) in *Meteorites and the Early Solar System II*, p. 584-624.
- [5] Marty B. et al. (2013) *Reviews in Mineralogy and Geochemistry*, 75, 149-181.
- [6] Levison H.F. et al. (2009) *Nature*, 460, 364-366.
- [7] Walsh K.J. et al. (2011) *Nature*, 475, 206-209.
- [8] Starkey N.A. et al. (2014) *Geochim. Cosmochim. Acta*, 142, 115-131.
- [9] Nakashima D. et al. (2012) *Earth Planet. Sci. Lett.*, 357-358, 355-365.
- [10] Nakashima D. et al. (2012) *Meteoritics Planet. Sci.*, 47, 197-208.
- [11] Boss A.P. et al. (2012) *Earth Planet. Sci. Lett.*, 345-348, 18-26.
- [12] Kruijer T.S. et al. (2014) *Science*, 344, 1150-1154.
- [13] Fujiya W. et al. (2013) *Earth Planet. Sci. Lett.*, 362, 130-142.
- [14] Sugiura N. and Fujiya W. (2014) *Meteoritics Planet. Sci.*, 49, 772-787.
- [15] Alexander C.M.O'D. et al. (2012) *Science*, 337, 721-723.
- [16] Yang L. et al. (2013) *Icarus*, 226, 256-267.
- [17] Cleaves L.I. et al. (2014) *Science*, In Press.
- [18] Alexander C.M.O'D. et al. (1998) *Meteoritics Planet. Sci.*, 33, 603-622.
- [19] Alexander C.M.O'D. et al. (2007) *Geochim. Cosmochim. Acta*, 71, 4380-4403.
- [20] Alexander C.M.O'D. et al. (2007) in *Protostars and Planets V*, p. 801-814.
- [21] Kebukawa Y. et al. (2011) *Geochim. Cosmochim. Acta*, 75, 3530-3541.
- [22] Alexander C.M.O'D. et al. (2013) *Geochim. Cosmochim. Acta*, 123, 244-260.
- [23] Herd C.D.K. et al. (2011) *Science*, 332, 1304-1307.
- [24] Alexander C.M.O'D. et al. (2014) *Meteoritics Planet. Sci.*, 49, 503-525.
- [25] Yabuta H. et al. (2007) *Meteoritics Planet. Sci.*, 42, 37-48.
- [26] Oba Y. and Naraoka H. (2009) *Meteoritics Planet. Sci.*, 44, 943-954.
- [27] Alexander C.M.O'D. et al. (2014) *Meteoritics Planet. Sci.*, In revision.
- [28] Dauphas N. and Pourmand A. (2011) *Nature*, 473, 489-492.