FROM DUST TO PLANETS: THE TALE TOLD BY MODERATELY VOLATILE ELEMENT DEPLETION (*MOVED*). Qing-zhu Yin, Department of Geology, University of California at Davis, One Shields Avenue, Davis, CA 95616, USA. yin@geology.ucdavis.edu

Introduction: The pronounced depletion of *m*oderately *v*olatile *e*lements (MOVE, that condense or evaporate at temperatures in the range 1350-650K) relative to the average solar composition is a characteristic feature in most primitive chondrites and bulk terrestrial planets (Fig. 1a). It differs from the composition of the Sun and from the materials further away from the Sun (CI chondrites). None of the remaining planets or even meteorites shows an enrichment of volatile elements that would balance the depletion in the inner Solar System. Whether this depletion occurred in solar nebular stage or in planetary formation stage has been the subject of long lasting debate. The search for "mysterite" initiated in 1973 [1] continues today "in search of lost planets"[2]. Here I show that the MOVED patterns demonstrate a clear connection between the rocky materials of the inner solar system and the interstellar dust. The inheritance of interstellar materials by the solar system is not only documented by the presence of presolar grains, various isotopic anomalies, but also expressed in the chemical element distribution in the inner solar system.

Data: The most widely used method in astronomy to study the chemical composition of interstellar dust grains has been to determine the gas-phase elemental abundances from the elemental absorption-line in the line of sight of stars, adopt a reference cosmic composition for the interstellar medium (ISM), which normally uses average solar composition, and then assume that what is depleted from the gas must be in the dust. The method covers a wide range of elements, including refractory and volatile elements, and it refers to the bulk composition of the grains rather than just the surface composition [3]. The absorption lines of most atoms and molecules found in the ISM occur at ultraviolet (UV) wavelengths, which requires their detection above the Earth's atmosphere. The Goddard High-Resolution Spectrograph (GHRS) aboard the *Hubble Space Telescope* (HST) has yielded the most precise abundance results for a range of interstellar environments, including gases in the local medium, in the warm neutral medium, in cold diffuse clouds, and in distant halo clouds. Plotted in Fig. 1b are three examples of such data [4.5]. Analyses of other diffuse-cloud lines of sight have shown that the pattern of depletion is nearly invariant from cloud to cloud.

When compared to meteoritic data in Fig 1a, the most obvious and striking feature is that the interstellar gas abundance is complemented by the meteorite data. Note that the complementarity of the MOVE seen in Fig. 1 is independent of condensation temperature. Complementarity holds even if elements are arranged in random order. Fig. 2 shows the ISM gas is anti-correlated with the primitive meteorite composition, independent of condensation temperature. Dust composition is calculated using $(X/H)_{dust}=(X/H)_{solar}-(X/H)_{gas}$, which is positively correlated with meteorite composition for MOVE (Fig. 3).

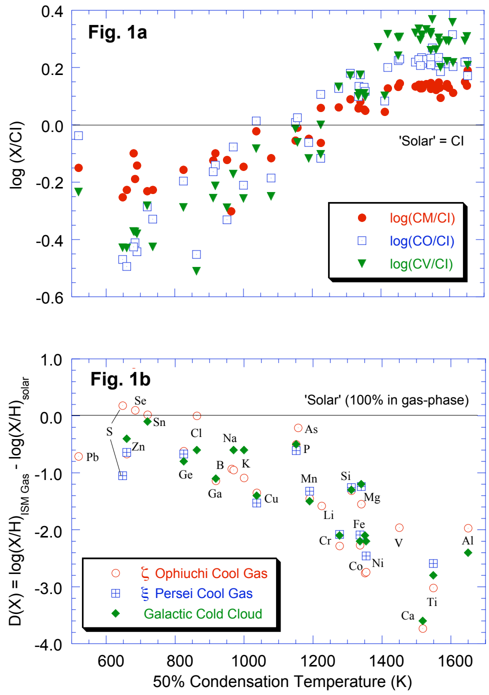

Fig. 1 (a) Elemental abundance data of primitive meteorites normalized to CI versus their 50% condensation temperature [6,7]. Only three carbonaceous chondrite groups are plotted for illustration purpose. The patterns for other groups of primitive chondrites and bulk terrestrial planets compositions are broadly similar. (b) Interstellar gas phase abundances relative to solar (CI) abundances vs. condensation temperature in Fig. 1b. The data sources are [4,5]. For MOVE, interstellar gas phase data is mirror imaged by the meteorite data

It is apparent from Fig. 1a and 1b that some of the MOVE (500-1100K) are depleted in both chondrites (log(X/CI)<0) as well as in the interstellar gas (D(X)<0]). This is also shown in Fig. 2 where the negative correlation between the ISM gas and the meteorite composition passes below zero, which represents the solar composition. This may be due to the fact that we used our Sun (=CI) as representative of "cosmic" abundance. There is growing evidence that our Sun is overabundant in most heavy elements by a factor of 1.6 compared to other representative stars in our Galactic neighborhood [3]. If the new standard reference value is adjusted to 0.6 solar level, elements with condensation temperatures between 500-1000K will not show significant depletion in both carbonaceous chondrites as well as in interstellar gas.

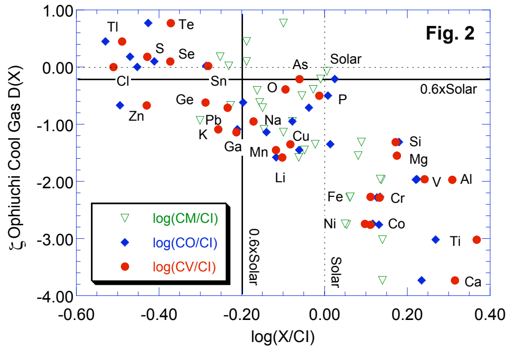

Fig. 2. For moderately volatile elements, the primitive meteorite composition (CM, CO, and CV groups are used as an example) is anti-correlated with the interstellar gas composition (ζ Ophiuchi Cool Gas is shown as an example).

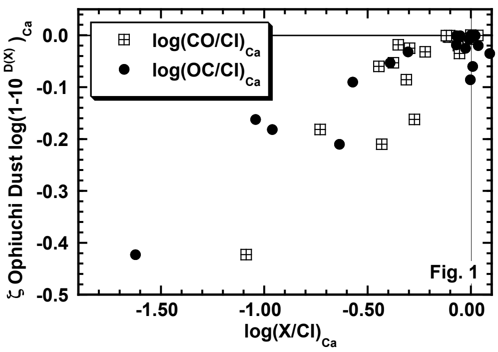

Fig. 3 ISM dust composition that is positively correlated with that of primitive meteorites for moderately volatile elements (CO and ordinary chondrite, OC, are used as examples). Dust composition is calculated from the observed ISM gas composition. ζ Ophiuchi Cool Gas is used as an example. Both data sets are normalized to CI and Ca.

Discussions: The solar nebula was formed by the collapse of rotating interstellar matter (gas and dust). The complementarity in Fig. 1 and the correlations in Fig. 2 and 3 lend themselves to a simple hypothesis that the fine dust from the ISM, *in cosmic proportion to gas*, makes up canonical solar composition in samples as large as the Sun and as small as the CI meteorite hand specimen. On the other hand, most rocky bodies of the inner solar system (between 0.38-5.2 AU) inherited the dust composition of ISM through coagulation, thermal annealing, and accretion of dust grains of interstellar origin which accumulated into bodies large enough (diameter>1km) to de-couple from the gas (without coalescing into the star) eventually evolving into planetesimals and planets. Evidences are mounting that the rapid grain growth occurs both during the molecular cloud stage as well as the solar nebula stage (e.g. [8, 9]). This implies reduced surface area and removing them from contact with the full volatile complements in the gas phase, increasing the possibilities to preserve the ISM chemistry in the dust aggregates.

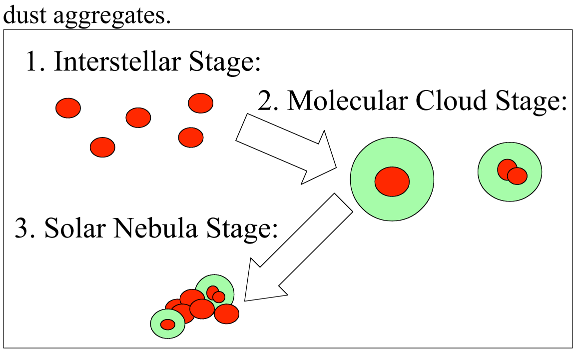

Fig. 4. The schematics of the inheritance model. (1) In the interstellar stage, the volatile elements are in hot ionized gas phase (not shown), while the refractory elements are locked in the dust grains (red); (2) In the cold and dense molecular cloud stage, the gas phase consists of H and He only. Organic-rich icy mantle (green) condenses with all the volatile elements on to the refractory core (red); (3) In the solar nebula stage, adiabatic compression or passage through a shock wave takes off the icy mantle. It is shown that the silicate core survives the entry into the solar nebula while the icy mantle with organics and other volatiles is largely destroyed [10], consistent with the primary mineralogy of chondrites being anhydrous. Progressive accretion of primary solids (ISM dust grains) as well as secondary solids (further processing of the primary solids within solar nebula, such as molten chondrules, condensates, evaporation residue, etc) lead all the way to planetesimals and planets. Proportion of green and red in stage 3 reflects the degree of moderately volatile element deletion. The model *does not* argue for massive survival of physical identities of presolar grains, but instead argue for discernible chemical links between the ISM dust and primitive chondrites (and terrestrial planets).

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