NEBULAR INGASSING OF WATER AND NOBLE GASES. Z.D. Sharp[1] and P.L. Olson[1], [1]Dept. Earth and Planet. Sci., University of New Mexico, Albuquerque, zsharp@unm.edu

Introduction: The source of volatiles to the Earth has been attributed to 1) incorporation of hydrous material during planetary growth (*e.g.*, pebble accretion); 2) late accretion of carbonaceous chondrites and 3) nebular ingassing directly from the primordial nebula. In this contribution, we build on our earlier work [1] to estimate the amount of water and noble gases that were introduced by ingassing in the presence of the solar nebula and subsequently by late accretion.

If the Earth reached more than ~27% of its present size before dissipation of the nebula, a high-pressure and high-temperature atmosphere would have developed. Our estimates, building on previous work [2, 3] suggest surface temperatures that would have exceeded the melting point for an ultramafic composition and pressures in excess of 200 bars (Fig. 1).

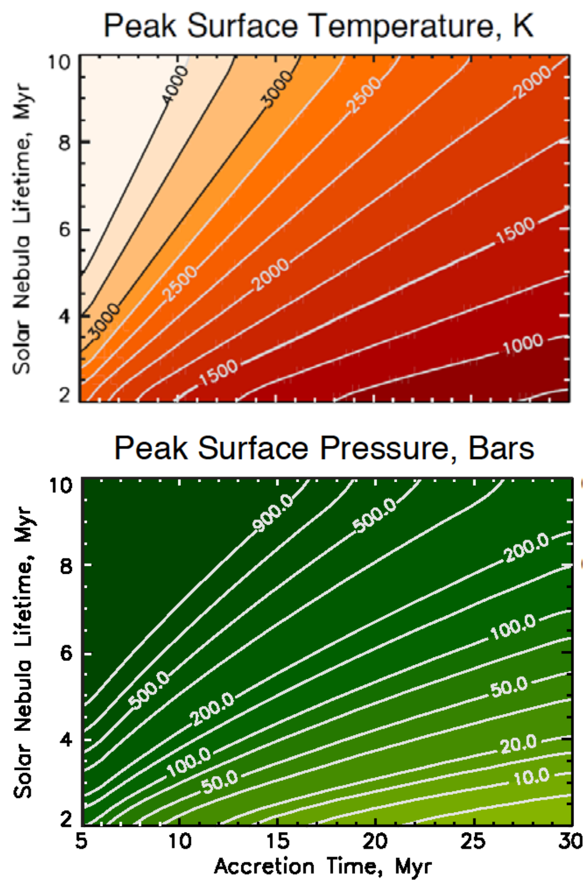

Fig. 1 Calculated peak temperature and pressures the Earth's surface in the presence of a nebular atmosphere.

The amount of H_2 and H_2O that were ingassed are a function of the oxygen fugacity ($f(O_2)$) at the atmosphere-surface interface, the duration of the solar nebula and the accretion rate for the Earth. We assume for these calculations that the solar nebula survived to ~ ½ the time for Earth accretion (*e.g.,* 5 My and 10 My, respectively). The calculated amount of hydrogen ingassed exceeds 6 ocean equivalents H_2O at IW-1 (Fig. 2). Implicit in these calculations is that even after the dissipation of the solar nebula, the accreted atmosphere of the Earth would still take millions of years to dissipate.

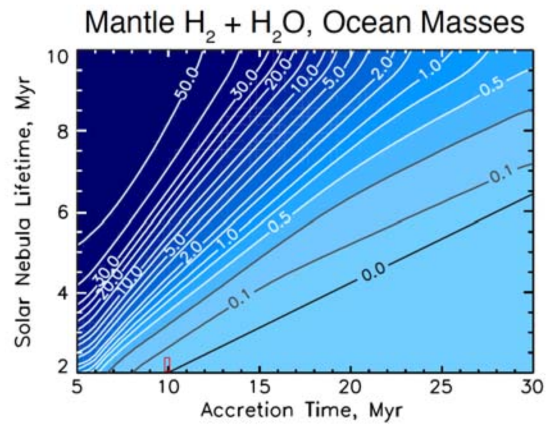

Fig. 2. Amount of total hydrogen ingassed for an $f(O_2)$ of IW-1.

Similar calculations can be made for the noble gases. The amount of ingassed ^3He is over 700 times the present-day estimates. This result is compelling evidence for a strong ingassed component. Other ideas for ingassed He include late delivery, but once the Earth reached 27% of its present size, impactors would be completely volatilized [4]. It is difficult to envision how volatilized He in a thin atmosphere could be incorporated into the deep mantle.

In contrast to the light rare gases, our calculations show that ingassing results in far less incorporation of the heavy noble gases Kr and Xe than what is thought to exist in the Earth today. Ingassing leads to an excess of He, Ne and Ar, and a deficit of Kr and Xe (Fig. 3). A semilogarithmic plot of (ingassed/present-day) concentrations of noble gases vs. the atomic mass shows a linear decrease for the three lightest noble gases. The linear fit is expected based on models of hydrodynamic escape [5] with the 0 intercept giving an m_c value of ~48, representing the mass above which hydrodynamic escape is negligible. The heavier rare gases require a late addition. We find that late addition of 1.3% CI chondrite *precisely* explains the deficit of Kr and Xe. The late addition would not add appreciably to the lighter rare gases, as they would tend to be lost to space.

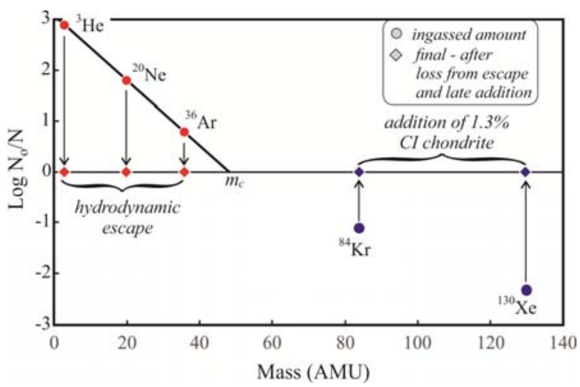

Fig. 3. Ratio of amount ingassed N_o to present-day terrestrial abundances (N) of noble gases. The light gases have a linear semi-log relationship consistent with significant hydrodynamic escape. The heavier gases require late addition of ~1.3 wt % chondrites.

Loss of H_2 gas will also occur once the atmosphere has eroded away. H_2 loss is a very effective method of raising the $f(O_2)$ of the magma ocean [6]. A loss of less than 1 ocean equivalent will raise the $f(O_2)$ from *IW-1* to *FMQ* (Fig. 4).

There are numerous geochemical studies that support the idea of significant nebular ingassing. The ^{20}Ne/^{22}Ne ratios of mantle plume sources match the solar nebula [7] and anomalously low D/H ratios from primitive plume sources are thought to represent primordial ingassing of nebular hydrogen [8]. Heavy rare gases also require a nebular component [9].

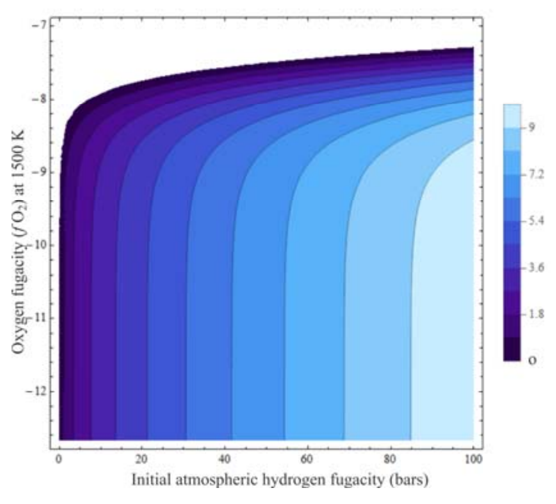

Fig. 4. Oceans of water remaining after H_2 loss as a function of rise in $f(O_2)$ from an initial value of IW-1 ($10^{-12.67}$). The $f(O_2)$ buffer becomes strong close to QFM ($10^{-8.5}$) due to the rapid increase in Fe^{3+}. The total amount of hydrogen ingassed at IW-1 is given at an $f(O_2)$ of $10^{-12.67}$.

Previous authors have suggested that the amount of ingassed volatiles is related to planetary size by a power function of the 3rd to 4th order [2, 3]. We find a similar relationship which leads to several important conclusions. First, the temperature of the Martian surface never exceeded the melting point of an ultramafic composition, so ingassing would not have occurred on Mars. Second, a planet that was even 2 times the size of Earth would have more than 10 times the amount of ingassed water. Under such conditions, the planet would be a 'water world' with ocean depths exceeding 100 km. Under such conditions, there would be no continental erosion, nutrient fluxes into the ocean would be greatly reduced and development of advanced life would likely be greatly curtailed. As a result, search for advanced life in exoplanets should focus on planets in the Earth-size range.

References: [1] Olson, P. and Sharp, Z.D. (2018) *EPSL 498,* 418-426. [2] Ikoma, M. and Genda, H. (2006) *Astrophys. J., 648*, 696-706. [3] Stökl, A., Dorfi, E.and Lammer, H. (2015) *Astronomy & Astrophys. 576,* 11 pages. [4] Tyburczy, J.A.,. Frisch, B and Ahrens, T.J. (1986). *EPSL 80,* 201-207. [5] Hunten, D.M., Pepin, R.O. and Walker, J.C.G. (1987) *Icarus 69,* 532-549. [6] Sharp, Z.D., McCubbin, F.M. and Shearer, C.K. (2013). *EPSL 380,* 88-97. [7] Williams, C.D. and Mukhopadhyay, S. (2018). *Nature 565,* 78-81. [8] Hallis, L.J., et al., (2015). *Science 350,* 795-797. [9] Porcelli, D., Woolum, D. and Cassen, P. (2001). *EPSL 193,* 237-251.