METEORITE OUTGASSING EXPERIMENTS AND THEIR CONSTRAINTS ON MODELING THE INITIAL ATMOSPHERES OF LOW-MASS PLANETS.

Maggie A. Thompson[1], Myriam Telus[2], Laura Schaefer[3], Jonathan J. Fortney[1], Toyanath Joshi[4], David Lederman[4] [1]Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, maapthom@ucsc.edu, [2]Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064, [3]Geological Sciences, School of Earth, Energy, and Environmental Sciences, Stanford University, Stanford, CA 94305, [4]Department of Physics, University of California, Santa Cruz, CA 95064

Introduction: At present, there is no first-principles understanding of how to connect a planet's bulk composition to its atmospheric properties. Since low-mass exoplanets likely form their atmospheres through degassing [1], a logical step to build such a theory for super-Earths and rocky planets is to assay meteorites, the left-over building blocks of planets, by heating them to measure the outgassed volatiles. Our Solar System presents a wide variety of meteorite types, including chondrites which are primitive unaltered rocks believed to be representative of the material that formed the rocky planets.

We present the current results of our meteorite outgassing experiments in which we heated a variety of CM carbonaceous chondrite samples at carefully controlled rates to temperatures from 200 to 1200 °C and measured the partial pressures and relative abundances of the outgassed volatile species (e.g., H_2O, CO, CO_2, H_2, H_2S, CH_4) as a function of temperature. Our experimental set-up consisted of a residual gas analyzer connected to a furnace to heat samples at specified rates. We compare the results of these experiments to Schaefer and Fegley's prior theoretical chemical equilibrium calculations which modeled thermal outgassing for a wide variety of chondrites to predict the composition of terrestrial atmospheres formed via outgassing of specific types of meteorites [2, 3]. In addition to testing and validating Schaefer and Fegley's models, the results from our experiments inform the phase space of chemical abundances used in atmospheric models of low-mass exoplanets.

Experimental Procedure: This study focuses on carbonaceous chondrites, and in particular the CM group, because they are some of the most pristine meteorite samples available and are representative of the material that was in the protoplanetary disk that subsequently accreted and formed the terrestrial planets [4, 5]. For this study, three chondrites are analyzed: Murchison, Jbilet Winselwan, and Aguas Zarcas [6, 7, 8].

In order to heat and measure the outgassed volatile components from meteorite samples, our experimental set-up consists of a furnace connected to a residual gas analyzer (RGA) and a turbopump vacuum system (Fig. 1). This system can heat samples at controlled rates to different temperatures (up to 1200 ºC) in a low-pressure (~10^{-5} Torr) environment and measures the partial pressures of up to 10 volatile species. For each experiment, we heat a sample from 200 to 1200 ºC at a rate of 3.3 ºC/minute. The RGA used in this study is a mass spectrometer that operates inside a vacuum chamber and ionizes a small fraction of the gas molecules according to their molecular masses up to 100 amu and measures their partial pressures. Since an RGA is commonly used for detecting low-levels of contamination in vacuum systems, its sensitivity to trace amounts of gas makes it ideal for carrying out this study [9]. The results from these experiments are partial pressures, mole fractions and relative abundances (reported in terms of mole fractions normalized to the total mole fraction of released gases, expressed as percentages) of outgassed volatile species from each meteorite sample as a function of temperature to which the samples are heated.

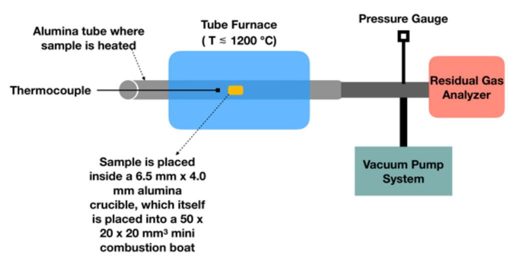

Fig. 1. Schematic of Instrument Set-Up. The furnace is connected to a turbopump which brings the entire system to a base pressure of ~5×10^{-5} Torr at room temperature and to an RGA which measures the partial pressures of up to 10 species continuously throughout the experiment.

Outgassing Experiment Results: Fig. 2 (top) shows the mole fractions of the measured volatile species as a function of temperature from the average of the three meteorite samples. By summing the relative abundances over temperature, we find that for all the samples H_2O has the highest abundance (~66 %) followed by CO (~17 %) and CO_2 (~16 %). H_2, H_2S, and the signals at 16 and 32 amu have lower abundances (< 2 %). In terms of the bulk elemental abundances outgassed, oxygen has the highest concentration (~80 %) followed by carbon (~11 %), hydrogen (~8.6 wt. %), and smaller amounts of sulfur and nitrogen (< 1%).

We expect the three meteorite samples, all being CM2 chondrites, to have similar outgassing abundances given their similar bulk compositions. Our experimental results confirm this prediction with the relative abundances for each species across the three samples being within 2σ of each other.

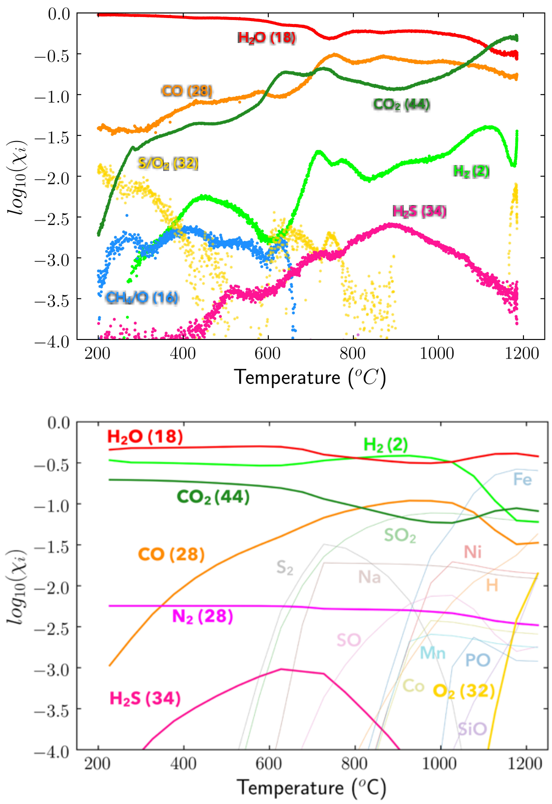

Fig. 2. Comparison between experimental results (top) and theoretical chemical equilibrium calculations (bottom) under the same pressure and temperature conditions. Top figure shows the experimental outgassing results for the average of the three CM chondrite samples measured. Bottom figure shows the outgassing abundances calculated assuming chemical equilibrium for an average CM chondrite bulk composition. The bold curves in the bottom figure correspond to species also measured in the outgassing experiments. The mass (in amu) of each species is in parentheses.

Comparison between Experimental and Theoretical Outgassing Compositions: Our outgassing experiments provide the first direct comparison to thermochemical equilibrium calculations that theoretically determine the outgassing composition of chondritic meteorites as a function of temperature and pressure. Chemical equilibrium calculations were performed using a Gibbs energy minimization code and include thermodynamic data for over 900 condensed and gaseous compounds of 20 major rock-forming and volatile elements [2, 3]. Fig. 2 (bottom) illustrates the results of chemical equilibrium calculations for outgassing an average bulk CM chondrite composition at the same pressure (1×10^{-5} Torr) and temperature range as our experiments. The bold curves in Fig. 2 (bottom) correspond to the same gaseous species measured in the outgassing experiments and the thin curves are for other volatiles that theoretically degas but that we do not currently measure in our experiments.

There are several similarities between the results from our experiments and those from the chemical equilibrium calculations. For instance, water is the dominant outgassed species over almost the entire temperature range for both experiment and theoretical calculation. In addition, CO_2 and CO outgas significantly from ~200 to 1200 ºC. Although H_2S has similar outgassing trends, it is predicted to outgas at lower temperatures assuming chemical equilibrium than it actually outgases in the experiments. This offset may be due to the fact that, in carbonaceous chondrites, sulfur can occur in gypsum which breaks down at 700 ºC and the corresponding phase change that has to occur for sulfur to outgas is kinetically inhibited which may not be fully accounted for in the chemical equilibrium calculations [10].

Implications for Low-Mass Planet Atmospheres: The results from our outgassing experiments have several important implications for the initial atmospheric chemistry of low-mass exoplanets. As low-mass planets form their initial atmospheres via outgassing during accretion, if the material being accreted is predominantly like CM carbonaceous chondrites, then H_2O-rich steam atmospheres will likely form. These atmospheres will also contain significant amounts of CO, CO_2, H_2, H_2S and species with mass numbers 16 and 32 amu. We suggest that models of the initial secondary atmospheres of low-mass planets should include these chemical species.

This work presents an experimental framework that takes an important step forward in connecting rocky planet interiors and atmospheres in which we utilize meteorites, the material representative of planet building blocks, to understand the phase space of initial outgassed atmospheric compositions. Ultimately, our results provide the first set of experimentally-determined initial conditions for outgassed atmospheric compositions and enable better assumptions to be made in low-mass exoplanet atmosphere models.

References: [1] Elkins-Tanton, L. T. & Seager, S. (2008) *ApJ*, 685, 1237-1246. [2] Schaefer, L. & Fegley, B. (2007) *Icarus*, 186, 462-483. [3] Schaefer, L. & Fegley, B. (2010) *Icarus*, 208, 438-448. [4] Lodders K. & Fegley, B. (1998) *The Planetary Scientist's Companion*. [5] Wasso, J. T. & Kallemeyn G. W. (1988) *Philosophical Transactions of the Royal Society of London*, 325, 535-544. [6] Krinov, E. L. (1969) *Meteoritical Bulletin*, no. 5, 2. [7] Ruzicka, A. et al. (2015) *Meteoritical Bulletin*, no. 102, 50. [8] Soto, G. J. et al. (2019), *Meteoritical Bulletin*, no. 108, in prep. [9] Stanford Research Systems (2009), *Operating Manual and Programming Reference: Models RGA100, RGA200 and RGA300 Residual Gas Analyzer*, 1.8 edition. [10] O'Brien, W. J. & Nielsen, J. P. (1959) *Journal of Dental Research*, 38, 541-547.