LEVERAGING METEORITE OUTGASSING EXPERIMENTS TO IMPROVE MODELS OF THE INITIAL ATMOSPHERES OF TERRESTRIAL EXOPLANETS. 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: Terrestrial exoplanets likely form their early atmospheres through outgassing during and after accretion [1]. However, there is currently no first-principles understanding of how to connect a planet's bulk composition to its initial atmospheric properties. We can gain important insights into this connection by assaying meteorites, which are leftovers of planetary building blocks (i.e., planetesimals) and provide some of the only such samples that can be probed directly in the laboratory. Our Solar System presents a wide variety of meteorite types, including chondrites which are believed to have similar compositions to the planetesimals that accreted to form the terrestrial planets [2]. In addition, a particular type of chondrites, carbonaceous chondrites, contain the highest proportions of volatiles relative to other remnant materials from terrestrial planet formation [3]. Although planet formation alters planetesimals through thermal and differentiation processes, carbonaceous chondrite-like material was likely an important source of volatiles for the Solar System's terrestrial planets, making these meteorites well-suited for studying early exoplanet atmospheres [4].

We present the results of our first set of meteorite outgassing experiments in which we use a mass spectrometer to measure the partial pressures and relative abundances of outgassed volatile species from CM carbonaceous chondrite samples over a wide temperature range. We compare our experimental results to theoretical chemical equilibrium calculations which model thermal outgassing for a variety of chondrites to predict the composition of terrestrial atmospheres formed via outgassing [5, 6]. The results from our experiments inform the chemical abundances used in models of the initial atmospheres of terrestrial exoplanets.

Samples, Experimental Procedure and Analysis: This study focuses on CM carbonaceous chondrites because their compositions are close to that of the solar photosphere and representative of the bulk composition of material in the protoplanetary disk during planet formation [3]. For this study, three CM chondrite samples are analyzed: Murchison, Jbilet Winselwan, and Aguas Zarcas [7, 8, 9].

In order to measure the outgassed volatile components from meteorite samples, our experimental set-up consists of a residual gas analyzer mass spectrometer connected to a furnace to heat samples at specified rates and a turbopump vacuum system to perform experiments in a high vacuum environment (10^{-8}-10^{-9} bars) [10]. For each experiment, we heat a sample from 200 to 1200 ºC at a rate of 3.3 ºC/minute and continuously monitor the partial pressures of 10 volatile species identified by their mass numbers. The results are partial pressures and mole fractions of outgassed volatiles as a function of temperature along with relative abundances summed over temperature (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.

Several factors must be accounted for to properly convert the raw mass spectrometry data to abundances of outgassed volatile gases. These factors include correcting for ion fragments, and adsorption and contamination from Earth's atmosphere, as well as the background signal. We correct for ion fragments and atmospheric adsorption using a set of linear equations. To account for the background signal, we conduct an additional experiment using the same procedure as that performed for the samples but with only the empty sample containers and then subtracting these background pressures from those of our samples.

Outgassing Experiment Results: Fig. 1 (top) shows the mole fractions of the measured volatile species as a function of temperature from the average of the three meteorite samples measured. In terms of relative abundances (which are summed over temperature), we find that for all three samples H_2O has the highest abundance (~62±8 %) followed by CO (~20±7 %), CO_2 (~17±5 %), with smaller quantities of H_2 and H_2S (<2 %) (uncertainties reported as 95% confidence intervals). Although we also monitor N_2 and species with mass numbers 12, 14, 16, and 32 amu, once we account for the data calibration factors mentioned above, their abundances are effectively 0. In terms of total elemental abundances outgassed, hydrogen has the highest concentration (~45±4 %) followed by oxygen (~42±2 %), carbon (~14±3 wt. %), and sulfur (< 1%).

Comparison between Experimental and Theoretical Outgassing Compositions: Our outgassing experiments provide the first set of laboratory results that simultaneously monitor the most abundant volatile species that are predicted to outgas to compare to thermochemical equilibrium calculations that predict the outgassing composition of chondritic meteorites.

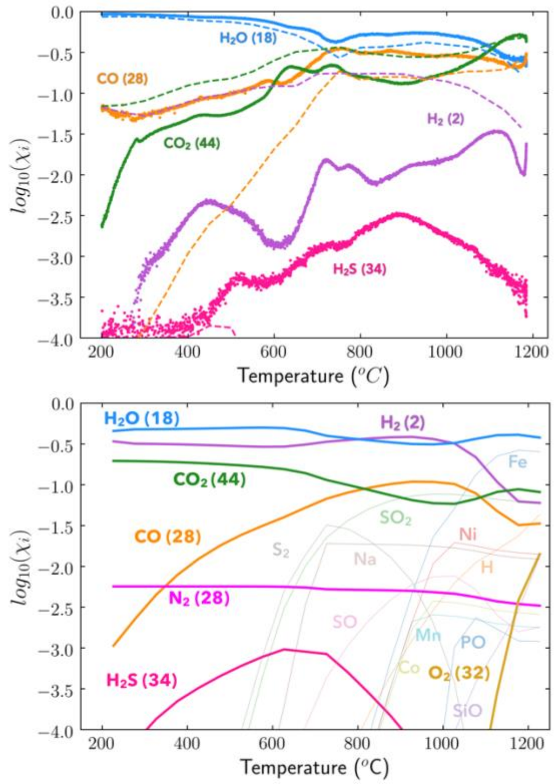

Fig. 1. Comparison between experimental results (top) and chemical equilibrium calculations (bottom) under the same pressure and temperature conditions. Top figure shows the average experimental outgassing results of the three CM chondrite samples measured. The dashed curves show 'equilibrium-adjusted' experimental abundances in which the equilibrium model was used to recalculate gas speciation using the experimental abundances at intervals of 50 ºC. 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, and the thin curves are for other volatiles that theoretically degas but that we do not currently measure in our experiments. The mass (in amu) of each species is in parentheses.

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 [4, 5]. Fig. 1 (bottom) illustrates the results of chemical equilibrium calculations for outgassing of an average bulk CM chondrite composition at the same pressure and temperature conditions as our experiments.

There are several similarities between the experimental and theoretical results. For instance, water is the dominant outgassed species and CO and CO_2 also outgas significantly over most of the temperature range for both experiment and theoretical calculation. In addition to the experimental results, we determined 'equilibrium-adjusted' abundances using the equilibrium model to re-compute gas speciation based on the experimental results (dashed curves in Figure 1 top). The 'equilibrium-adjusted' H_2O and CO_2 abundances (and CO at higher temperatures) provide a better match to the equilibrium model results. However, there are also significant differences. For example, H_2 is the second most abundant outgassing species according to equilibrium models with maxima mole fractions of ~0.4 but our experimental results give an order of magnitude lower average H_2 outgassing mole fraction of ~0.03. This difference may be due to the fact that our experiments do not allow sufficient time for some gas-go Improve as reactions to take place that could raise the H_2 abundance, which is further supported by the 'equilibrium-adjusted' H_2 abundances. (For a discussion of H_2S see [10].)

Implications for Terrestrial Planet Atmospheres: The results from our outgassing experiments have important implications for the initial atmospheric chemistry of terrestrial exoplanets. As rocky planets form their initial atmospheres via outgassing during accretion, if the material being outgassed is predominantly like CM carbonaceous chondrites, then H_2O-rich steam atmospheres will likely form. These atmospheres will also contain significant amounts of CO, and CO_2. Accordingly, we suggest that models of the initial atmospheres of terrestrial planets should include these chemical species.

This work presents an experimental framework utilizing meteorites that takes an important step forward in connecting rocky planet interiors and early atmospheres. Ultimately, our results provide the first set of experimentally-determined initial conditions for outgassed atmospheric compositions and enable better assumptions to be made in terrestrial exoplanet atmosphere models.

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