

## OUTGASSING COMPOSITION OF THE MURCHISON METEORITE: IMPLICATIONS FOR VOLATILE DEPLETION OF PLANETESIMALS AND TERRESTRIAL EXOPLANET ATMOSPHERES

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**Introduction:** With the launch of NASA's James Webb Space Telescope, exoplanet science is entering a new technological era that will enable us to begin characterizing terrestrial exoplanets including their atmospheres and formation histories. In preparation for the upcoming observational data, we need suitable theoretical tools, informed by experimental data, to model the expected diversity of these planets. A strong theoretical basis for the formation, bulk composition and atmospheric properties of terrestrial planets requires an understanding of their possible building block materials. For the foreseeable future, the only direct analog building-blocks of terrestrial planets in our Solar System and potentially in other planetary systems that can be rigorously studied in the laboratory are meteorites. Since meteorites are some of the only samples that are compositionally representative of material in the protoplanetary disk during planet formation and terrestrial planets likely form their early atmospheres via outgassing during accretion [1], meteorites can inform the connection between terrestrial bodies (both planets and planetesimals), the loss of their volatiles and their early outgassed atmospheres.

Theoretical studies have modeled the outgassing compositions of primitive meteorites under chemical equilibrium conditions to inform terrestrial bodies' initial atmospheres [2, 3]. To provide experimental constraints to this work, we previously conducted a set of outgassing experiments on CM chondrites in which the abundances of various outgassing species (e.g., H<sub>2</sub>O, CO, CO<sub>2</sub>) were measured as a function of temperature to which the samples were heated (up to 1200 °C) [4]. However, these experiments were limited in their ability to measure all of the elements that are predicted to outgas according to chemical equilibrium models (e.g., Na, Fe, S, Ni, Co, P and Mn). Therefore, to fill this gap, we performed a new series of heating experiments and subsequent bulk element analyses on Murchison samples to experimentally determine the broader elemental outgassing trends.

We present the bulk elemental compositions of Murchison samples heated to different temperatures (400, 600, 800, and 1000 °C). Combining these new bulk element measurements with our prior set of outgassing experiments provides a more complete under-

standing of Murchison's outgassing composition and has implications for the formation and evolution of planetesimals and terrestrial planet atmospheres.

**Heating Experiments and Bulk Elemental Analysis:** This study utilizes powdered samples of Murchison, a CM2 carbonaceous chondrite, because its composition is volatile-rich and representative of the bulk composition of material in the protoplanetary disk during planet formation [5, 6].

We used two furnaces to perform the heating experiments under different pressure regimes: one operates at atmospheric pressure and the second operates under high vacuum ( $\sim 10^{-4}$  Pa). With each furnace, we performed a series of experiments in which we heated 4-5 mg powdered Murchison samples to 400, 600, 800 and 1000 °C at a rate of 3.3 °C/min and held each sample at its peak temperature for 5 hours. After each heating experiment, we saved the residue samples for bulk element analysis. We performed two complete sets of heating experiments with the furnace at atmospheric pressure (i.e., 8 Murchison samples, 2 heated to 400 °C, two heated to 600 °C, etc.) and one set of heating experiments with the furnace under vacuum.

We digested two unheated Murchison samples, all of the residues from the stepped-heating experiments and several rock standards for bulk element analysis. A magnetic sector high-resolution inductively-coupled plasma mass spectrometer (ICP-MS) analyzed the isotopic compositions of the samples. To quantify the elemental concentrations of the Murchison samples, we created four-point calibration curves with the rock standards to relate elemental abundances to measured isotope intensities from the ICP-MS. Using these calibration curves, we calculated the concentrations (ppm) of Al, Ti, Ca, V, Ni, Co, Mg, Fe, Cr, P, Mn, Na, Zn, and S for all of the Murchison samples.

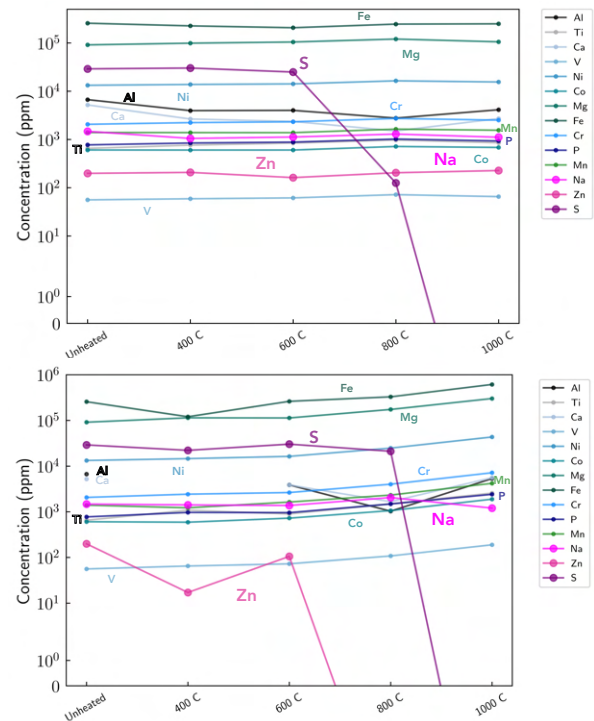
**Results:** Fig. 1 (top) shows the average elemental concentrations of the unheated Murchison samples and the residues from the two sets of stepped-heating experiments performed at atmospheric pressure. Fig. 1 (bottom) shows the average elemental concentrations of the unheated Murchison samples and the residues from the set of stepped-heating experiments performed under vacuum conditions. For the heating experiments performed at atmospheric pressure, 11 of the 12 meas-

ured elements (Ti, V, Ni, Co, Mg, Fe, Cr, P, Mn, Na, Zn) did not change significantly in concentration between the unheated samples and the residues from each of the stepped heating experiments. However, sulfur varied considerably over the course of these heating experiments, with significant decreases in its concentration for residues heated to 800 and 1000 °C. This decrease in S's concentration suggests that significant outgassing of S occurred during the heating experiments at 800 and 1000 °C at atmospheric pressure.

For the heating experiments performed under vacuum, while the concentrations of Ti, V, Ni, Co, Mg, Fe, Cr, P and Mn also did not vary significantly across these samples, S, Zn and Na decreased in their concentrations. For the residue heated to 1000 °C, its S concentration was below the detection limit, suggesting significant outgassing of S during this experiment. In addition, Zn also significantly outgassed during this set of heating experiments with its concentration decreasing below the detection limit for the residues heated to 800 and 1000 °C. Finally, Na's concentration decreased slightly for the residue heated to 1000 °C, indicating that slight outgassing of Na may have occurred at the highest temperature.

**Comparison with Prior Experiments:** Combining these new bulk element measurements of Murchison with our previous set of experiments that measured outgassing of highly volatile species, we gain a more complete understanding of Murchison's outgassing composition at temperatures from 400 to 1000 °C. The findings from [4] determined that Murchison outgasses significant amounts of H<sub>2</sub>O, CO, CO<sub>2</sub> and smaller amounts of H<sub>2</sub> and H<sub>2</sub>S up to 1200 °C under vacuum conditions. This new study confirms the H<sub>2</sub>S outgassing trends of [4], showing that sulfur begins outgassing at 800 °C and significant outgassing occurs at 1000 °C. In addition, this study demonstrates that Zn (and to a lesser extent Na) is expected to outgas at temperatures above 800 °C under vacuum conditions.

**Implications for Planetesimals and Terrestrial Planet Atmospheres:** Combined with our previous outgassing experiments, the results of this study have several important implications for the volatile depletion patterns of planetesimals and the early atmospheres of terrestrial planets. If undifferentiated planetesimals with CM-chondrite-like compositions are heated to temperatures near 1000 °C during formation and accretionary evolution, the initial outgassing composition will likely be composed of at least H, C, O, S, Zn and possibly Na. Therefore, these planetesimals will likely become depleted in some portion of these elements unless there is a mechanism that allows them to retain these outgassed species. Our study also suggests that surface pressure may influence the



**Fig. 1. Average elemental concentrations (ppm) of the unheated Murchison samples and the residues from the stepped-heating experiments at atmospheric pressure (top) and those under vacuum (bottom).** The y-axis shows the concentration (ppm) for each element (labeled by color) for the unheated samples and the residues from the heating experiments (x-axis, labeled either “Unheated” or by the temperature to which the samples were heated). Since S, Na and Zn were the elements whose concentrations varied the most throughout the stepped-heating experiments, their labels are larger and in a different color scheme than the other elements.

temperatures at which certain elements degas. For example, for the samples heated at atmospheric pressure, S degassed at 800 and 1000 °C but Zn and Na did not outgas over this temperature range. Conversely, for the samples heated under vacuum, S and Zn (and Na slightly) outgassed at these higher temperatures.

With regards to terrestrial planets’ initial atmospheres, if the bulk composition of material being outgassed from a terrestrial planet is similar to that of Murchison, this study demonstrates that sulfur and zinc (and smaller amounts of sodium) are expected to outgas at temperatures above 800 °C. Ultimately, this study provides models of volatile depletion of undifferentiated planetesimals and initial atmospheres of terrestrial planets with experimental constraints.

**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] Thompson, M. A. et al. (2021), *Nature Astronomy*, 5, 575. [5] Krinov, E. L. (1970) *Meteoritics*, 5, 85. [6] Lodders K. & Fegley, B. (1998) *The Planetary Scientist's Companion*.