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Headline Article
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Heating Meteorites to Understand Exoplanet Atmospheres

--- Heating carbonaceous chondrites in a vacuum oven provides constraints on the origins of the atmospheres of Earth-like planets around other stars.

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Astronomical observations, especially those from NASA's Kepler mission, show unambiguously that planets orbit other stars. Hundreds of them appear to be Earth-like in size and many orbit their stars at distances suitable for the presence of liquid H_2O, a key ingredient for life. The main observations we will have, as advanced space- and ground-based telescopes start looking, are of the atmospheres of those Earth-like planets. So understanding the links between the abundances of volatile species inside those planets and in the planetary atmospheres is crucial to understanding formation of Earth-like exoplanets and the possibilities for life on them. Theoretical calculations have been done to explore the range of possible atmospheric compositions expected for atmospheres formed by extraction of gases from the interior. These are fascinating guides for future observations but lack experimental data to quantify the outgassing processes. Maggie Thompson (a graduate student at the University of California, Santa Cruz) and colleagues at UC Santa Cruz have taken a major step in solving this knowledge gap by heating volatile-rich CM carbonaceous chondrites in vacuum and determining via mass spectrometry what gases are released and the temperatures at which they are released. They find that the liberated gases are dominated by H_2O (on average 66% of the total gas released), along with smaller but significant amounts of carbon monoxide (CO, 18%), carbon dioxide (CO_2, 15%), and smaller amounts (about 1%) of hydrogen (H_2) and hydrogen sulfide (H_2S). These are the first data to give a complete picture of gas compositions released into evolving atmospheres early in the histories of Earth-like exoplanets and provide an important starting point for understanding the compositions and habitability of other worlds far far away.

Reference:

- Thompson, M. A., Telus, M., Schaefer, L., Fortney, J. J., Joshi, T., and Lederman, D. (2021) Composition of terrestrial exoplanet atmospheres from meteorite outgassing experiments, *Nature Astronomy*, doi: 10.1038/s41550-021-01338-8. [**article**]

Exoplanets and their Atmospheres

Two Swiss astronomers, Michel Mayor and Didier Queloz, won the 2019 **Nobel Prize in Physics** because of, in the words of the Nobel Academy, "the discovery of an exoplanet orbiting a solar-type star" for astronomical research they did in the mid-1990s. (**Exoplanets** are planets orbiting stars other than our Sun.) An interesting 2019 opinion piece in *Scientific American Observations,*, "**Who Really Discovered the First Exoplanet?**" by Joshua N. Winn gives more information about earlier reports of possible exoplanet discoveries. Additional observations from ground-based telescopes found about a hundred exoplanets, but the Kepler space telescope mission increased that number to over 4,000 exoplanets. For a summary of how exoplanets are found and information about the mission go to the **Kepler mission overview** and read about **Kepler's legacy of discoveries**.

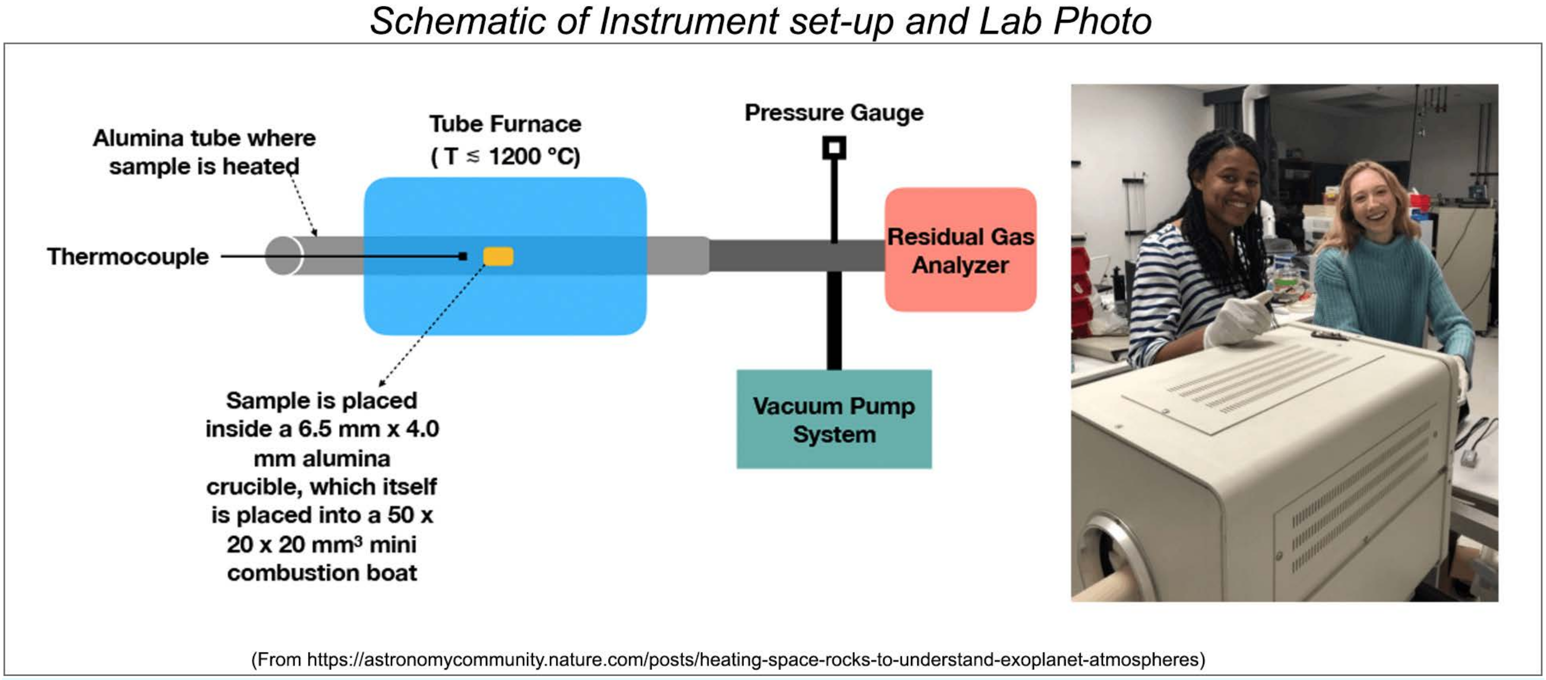
Kepler has run out of gas but will soon be replaced by NASA's James Webb Space Telescope and the European Space Agency's PLATO space telescope. In addition, improved ground-based telescopes (large and with advanced instrumentation) are also coming online during the next decade or so, all of which will lead to a vastly improved inventory of exoplanets and more information about their compositions. It will likely be possible to characterize the composition of an exoplanet atmosphere, making it possible to understand exoplanet composition, formation, and geologic evolution. The promise of new data will lead to additional modeling of the origins of exoplanet atmospheres, especially for those in Earth's size range (smaller than Jupiter and the other gas giants, larger than asteroids). One problem with modeling gas escape from planetary interiors during formation of a primary atmosphere is that we have no experimental data on what happens when a **volatile**-bearing region of a planetary interior is heated. What gases are released and migrate to the surface? How does the gas mixture change with temperature? Were the full set of likely gas components measured? Maggie Thompson and coworkers set out to fill this gap in our knowledge by studying what gases are released when analog rocks are heated. Following an established and productive practice in cosmochemisty, they turned their attention to meteorites.

Heating Primitive Carbonaceous Chondrites

The first step in Thompson's plan for understanding the initial composition of planetary atmospheres was to choose appropriate meteorites to use in heating experiments. The obvious choice was CI or CM **carbonaceous chondrites**, the most **primitive** extraterrestrial materials in our collections. Of course, this necessitated assuming (and maybe hoping?) that the meteorites represent the composition of primitive solar system materials. This is a safe assumption because the elemental abundances of these meteorite types match the composition of the Sun's photosphere, which has been analyzed thoroughly by astronomical **spectral** measurements. This remarkable compositional match shows that CM chondrites represent a reasonable measure of the bulk chemical composition of the **solar nebula**, the dusty haze that surrounded the proto-Sun and in which the planets formed. Equally important, CM chondrites have high concentrations of volatile materials, including H_2O and organic compounds, making them likely candidates for representing the chemical compositions of the **planetesimals** that accreted to form the planets.

Maggie Thompson and her advisor Myriam Telus acquired specimens of three CM chondrites: Murchison (**Meteoritical Database link**, observed to fall in Australia in 1969), Jbilet Winselwan (**Meteoritical Database link**, found in the western Sahara in 2013), and Aguas Zarcas (**Meteoritical Database link**, fell in Costa Rica in 2019). The meteorite find samples were chosen to minimize contamination from weathering on Earth. As further assurance that the samples were not contaminated by exposure to Earth's atmosphere or during entry, none of the samples contained any **fusion crust** (the melted portion formed when meteoroids blaze through the Earth's atmosphere). The samples were ground in an agate mortar and pestle and sieved so the grains were between 20 and about 100 micrometers in size; the fine grain size ensured that the powders were homogeneous. The powders were stored in a desiccator held under vacuum to further guarantee there was no contamination. Interested readers can see photographs of the meteorites on Maggie Thompson's engaging and clear blog post about the work, "**Heating Space Rocks to Understand Exoplanet Atmospheres**" at the Nature Portfolio Astronomy Community site.

The experiments involved heating small samples of meteorite powder (about 3 milligrams) in a furnace connected to a **mass spectrometer**. The whole system was pumped down to a pressure of between 10^{-9} bars (a billionth of atmospheric pressure) before heating to 10^{-8} bars (one hundred millionth of atmospheric pressure at the highest temperature used (1200°C). Each sample resided in an open crucible and was heated from 200 to 1200°C, with the temperature increasing at a rate of 3.3°C per minute. The partial pressure of each gas species released was measured using a Residual Gas Analyzer (RGA) mass spectrometer, which fundamentally measures the partial pressure at specific atomic mass units (e.g., H is 1, H_2 is 2, CO is 28). RGAs are often used for monitoring contamination during some industrial processes, so they are both rugged and able to measure small quantities of gases. Thompson used an experimental set up in co-author David Lederman's laboratory in the UCSC Westside Research Park, an arm of the UCSC Department of Physics at UC Santa Cruz. The system included a high-temperature furnace connected to a RGA and vacuum pumping system (see diagram of the system below). During a heating experiment the gases were continuously removed by the vacuum pump, creating the realistic system of gas removal from a planet's interior into its developing atmosphere.


Schematic of Instrument set-up and Lab Photo

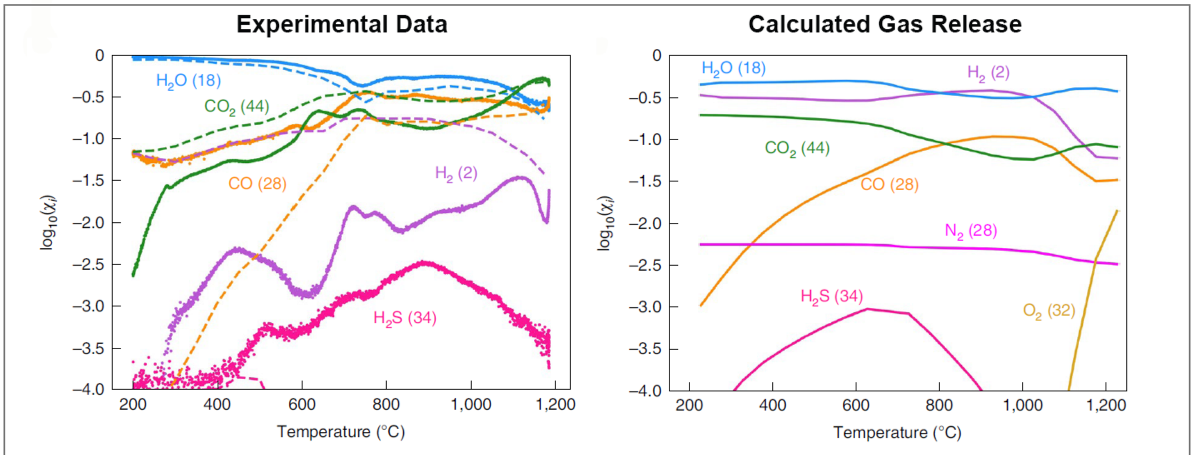
(From https://astronomycommunity.nature.com/posts/heating-space-rocks-to-understand-exoplanet-atmospheres)

Schematic of the instrument set-up used for the experiments. A tube made of alumina is used to insert an alumina crucible into the furnace. (Alumina, Al_2O_3, is a relatively unreactive material that withstands high temperatures without either melting or reacting with the powdered samples.) The temperature of the furnace can be increased linearly to determine the relative abundances of gases released as a function of temperature. Myriam Telus (left) and Maggie Thompson (right) are shown next to the instrument.

The results of the measurements are enlightening. The graphs below show the amount of different gaseous molecules released as a function of temperature for the average of the heating measurements for all three CM chondrites, and compared to the gas release modeled using thermodynamic calculations assuming equilibrium and the amount of H, C, O, and S in CM chondrites. The graphs have the same axes and ranges, with temperature in Celsius on the x-axis and the abundance (in mole fractions) of each gas species on the y-axis. The abundances are given on a logarithm scale. At a given temperature the mole fractions need to add up to 1.0, allowing Maggie Thompson to determine the percentages of each gas component present in the furnace's atmosphere as a function of temperature. H_2O starts out just below the 0.0 (which means 1.0 in non-logarithm units) in the diagram, indicating it is the dominant molecule released.

The amount of each gas released varies with temperature, showing that when a planet with CM chondrite abundances of volatiles was heated its atmosphere would change with time. When deconvolved into percentages, the total gas released over the entire temperature range is dominated by H_2O (on average 66% of the total gas released), along with smaller but significant amounts of carbon monoxide (CO, 18%), carbon dioxide (CO , 15%), and smaller amounts (about 1%) of hydrogen (H_2) and hydrogen sulfide (H_2S). The gas release patterns for the calculations are broadly similar for the experimental and calculated cases. For example, H_2O is the most abundant gas released. However, there are significant differences, too. These differences are due in large part to continuous removal of the gases in the experiments (called an open system) whereas the calculations assume no loss of gas and continuous adjustments in the specific molecules present due to chemical reactions (called a closed system).

Comparison of Experimental and Theoretical Results for CM Chondrites



(From Thompson, M. A., *et al.*, 2021, *Nature Astronomy*, doi: 10.1038/s41550-021-01338-8.)

These graphs show the average abundances (in mole fractions) of gases analyzed during experiments on the three CM chondrites studied (left) compared to theoretical calculations of gas release starting with the bulk chemical composition of CM chondrites (right). The experiments were done under conditions of continuous pumping, hence represent chemical behavior in an open system; the calculations assume a closed system. The open system experiments are more like the real system of planetary heating. The numbers after the species names are the molecular atomic mass units (e.g., H_2O is two times 1 for hydrogen plus one times 16 for oxygen, giving a total, the amu, of 18).

Only the Beginning

These experiments are quite timely, considering the exciting new observations of other planetary systems that will be made by great new telescopes in space and on the ground. New observations will be enhanced by new modeling of how atmospheres on Earth-like planets formed, but the modeling will include a much better understanding of which gases and how much of each of them will escape from the interiors. The Team Thompson experiments provide sound empirical data on what happens when planets form and heat up, expelling their volatile contents to produce water-rich atmospheres. It is a first step in understanding the link between observations of the atmosphere surrounding an Earth-like exoplanet and the composition of the exoplanet's interior. Some authors have suggested that other types of meteorites such as **enstatite chondrites** might be the main source of volatiles for the growing Earth, requiring additional outgassing experiments to predict what the atmospheric compositions could have been. There are a lot of chondrite types, hence a lot of experiments to be done. This is an exciting time with new observations of exoplanets and additional experiments on possible starting materials.

Additional Resources

Links open in a new window.

- Thompson, Maggie A., Telus, Myriam, Schaefer, Laura, Fortney, Jonathan J., Joshi, Toyanath, and Lederman, David (2021) Composition of terrestrial exoplanet atmospheres from meteorite outgassing experiments, *Nature Astronomy*, doi: 10.1038/s41550-021-01338-8. [**article**]

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