The Prospect of Detecting Volcanic Signatures on an ExoEarth Using Direct Imaging

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Introduction: The atmospheres of terrestrial exoplanets have recently become accessible through the James Webb Space Telescope (JWST) by using both transmission and emission spectroscopy. These techniques can detect the chemical species in an exoplanet atmosphere, which can be input into three-dimensional (3-D) general circulation models (GCM) to estimate the planet's climate. Determining the state of exoplanet interiors is also essential for understanding their climates since we know tectonic activity on Earth catalyzed by its active interior has been an essential factor for maintaining a stable climate. Since resolving the surfaces of exoplanets is an impossibility with current technologies, we will have to rely on indirectly inferring an active interior from evidence of volcanism in their atmospheres (1, 2). Common chemical indicators of volcanic activity that can be observed in atmospheric spectroscopy are absorption from sulfur dioxide (SO2) and sulfate aerosols.

The capabilities of JWST make it able to perform atmospheric spectroscopy on terrestrial exoplanets around smaller M-type stars, however terrestrial planets in systems like the solar system will be beyond its sensitivity. Future facilities with coronagraphs will provide the opportunity to investigate the atmospheres of Earth analogs given the system is sufficiently close so that the star and planet can be resolved. Our project includes a multitude of reflected light spectra of a volcanically active exoEarth analog assuming it is observed by a 6m LUVOIR-like instrument with an attached coronagraph. Here we provide an overview of the model used to simulate eruptions on the exoEarth, how we simulated its reflectance spectra, and what features within the spectra may be the best indicators of volcanism.

Modelling Volcanism and Reflectance Spectra: Using the Goddard Earth Observing System Chemistry Climate Model (GEOSCCM; 3) we modelled eruptions from large igneous provinces on Earth and the resulting changes in Earth's atmosphere after the eruptions. We consider 4 different eruption cases that inject 60, 30, 15, and 1.8 gigatons (Gt) of SO2 into the atmosphere. The model simulates these eruptions by injecting SO2 into the lower atmosphere and the upper stratosphere every 3 months over a 4-year period. The eruptions are then stopped and ran for an additional 4 years to study how the atmosphere recovers from the eruptions. We also conducted a baseline simulation of Earth for 1 year without any eruptions. GEOSCCM models the chemical and photolysis reactions caused by the addition of SO2 into the atmosphere. From the model we obtained 3-D monthly averaged atmospheric temperature, pressure, and chemical abundance data for each of the 4 eruption simulations, and the baseline simulation.

To simulate the reflectance spectra of the GEOSCCM volcanic Earth as an exoplanet we used the Global Emission Spectra (GlobES) application which is part of the Planetary Spectrum Generator (PSG) radiative transfer suite. GlobES can utilize the output from 3-D GCM simulations to simulate reflected light spectra of a planet that incorporates the effects of an inhomogeneous atmosphere and surface. We defined the exoEarth to be an exoplanet orbiting a G-type star at 1 AU with a phase angle of 90 degrees and the star being 10 pc away from the observing instrument. The hypothetical instrument we used for the observations is LUVOIR-B with a 6-meter mirror and attached coronagraph. The atmosphere of the planet was defined using the monthly averaged outputs from GEOSCCM which includes 3-D temperature, pressure, and chemical abundance profiles. Reflectance spectra were simulated for every month of all 4 eruption cases, and the baseline case.

Results: Figure 1 displays the reflectance spectra for every 6 months of the 30 Gt eruption case in both log-space (upper panel) and linear-space (lower panel). Major spectral features in the spectra are caused by ozone (O3), oxygen (O2), and water vapor (H2O). The O3 feature at 0.25 microns continuously decreases during the first 4 years of the simulation while the eruptions are ongoing. Once the eruptions cease, the abundance of O3 begins to replenish and the O3 absorption feature begins to increase in size. In the lower panel of Figure 1, the slope of the spectra becomes steeper as the eruptions are occurring. This change in slope is caused by the production of sulfuric acid (H2SO4) haze which is effective at scattering light at those wavelengths. After the eruptions stop, the H2SO4 haze begins to be removed from the atmosphere and the slope begins to subside.

The force from the eruptions transported H2O from the troposphere into the lower stratosphere. This increase in H2O would typically result in larger absorption features, however the features at 0.9, 1.1, 1.3, and 1.8 microns are initially flattened because the H2SO4 haze mutes H2O absorption. Once the haze begins to be removed, the H2O features begin to increase in size, and eventually become larger than those in the baseline spectrum.

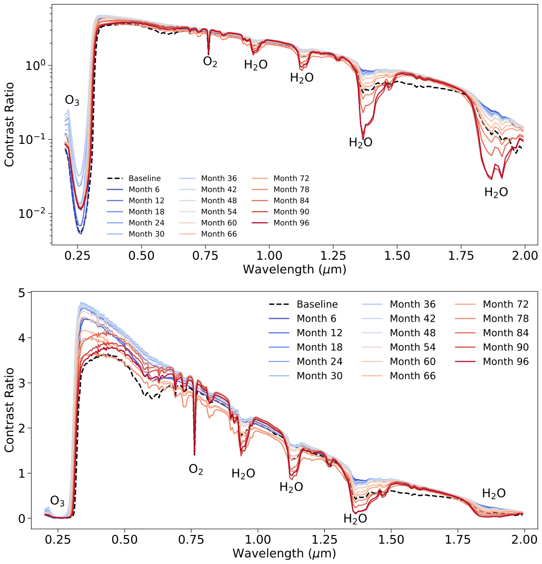

Figure 1: The reflected light spectra for every 6 months of the 30 Gt eruption simulation in comparison to the averaged baseline spectrum. The upper and lower panels display the same spectra, but the upper panel shows contrast ratio in log-space, while the lower is linear. Spectral features are labelled with their respective molecular absorbers.

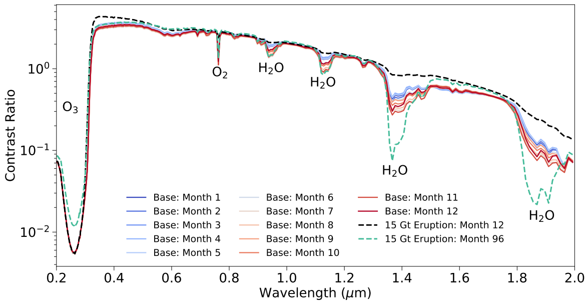

Figure 2: The reflectance spectra of the baseline simulation compared to the 15 Gt eruption spectrum when the features are both largest and smallest.

We concluded that the most distinct signs of volcanic activity in a reflectance spectrum are fluctuations in the sizes of O3, H2O, and O2 absorption features, as well as the sharp peak which forms at 0.4 microns. We compared the fluctuation of the absorption features in the eruption simulations to that of the baseline simulation to determine whether seasonal variability can cause similar changes in absorption feature size as is seen in the eruption cases, which is illustrated for the 15 Gt eruption in Figure 2. We found that the baseline spectrum has no variation in the size of the O3 feature, but the H2O feature can have comparable variation in its size because of seasonal changes to the atmosphere. Lastly we determined the observation time required for the hypothetical LUVOIR instrument to detect all major absorption features. It was determined that the O3 feature could be consistently detected in as little as 6 hours of observation. Since the size of the H2O features vary so greatly, they vary from being undetectable to being detected in as few as 9 hours of observation.

References: [1] Misra, Amit, et al. "Transient sulfate aerosols as a signature of exoplanet volcanism." *Astrobiology* 15.6 (2015): 462-477. [2] Kaltenegger, L., W. G. Henning, and D. D. Sasselov. "Detecting volcanism on extrasolar planets." *The Astronomical Journal* 140.5 (2010): 1370 [3] Guzewich, Scott D., et al. "Volcanic Climate Warming Through Radiative and Dynamical Feedbacks of SO2 Emissions." *Geophysical Research Letters* 49.4 (2022): e2021GL096612.