Mineral and chemical detail of rocky exoplanet surfaces could be detectable

Many rocky exoplanets are likely to be basaltic. Now, models of laboratory emission spectra of basaltic rocks suggest that JWST and future observatories could detect specific mineral and chemical signatures on these exoplanets. When present at high abundances, minerals indicative of rock–water interactions are particularly visible in modelled planetary flux spectra.

The question

An outstanding question in exoplanet science is how much compositional detail of rocky exoplanet surfaces can be ascertained from space telescope observations. That this question can even be asked is thanks to the new era of mid-infrared exoplanet science, heralded by the Spitzer Space Telescope and accelerated by the success of the James Webb Space Telescope (JWST). Until recently, scientists could theorize about the composition of rocky exoplanet surfaces[1], but there were no data pertaining to the geologic record of their formation and evolution. Now there are mid-infrared observations of at least four rocky exoplanets, and for each planet the data are consistent with a surface made of the dark, iron-and-magnesium-rich rock called basalt[2,3] — the same rock type that constitutes the crust of Earth's ocean basins. This is already unprecedented detail, but lavas can range widely in mineralogy and bulk chemistry while still fitting under the general 'basalt' umbrella. Thus, we set out to investigate how much additional geological detail might be possible to elucidate from JWST data.

The observation

Because we were interested in geological detail, we used 15 real basaltic rocks from Earth as the basis of our study. We characterized their bulk geochemistry and mineralogy using X-ray fluorescence and X-ray diffraction, respectively. Then we measured the mid-infrared emissivities of the samples using a Fourier transform infrared spectrometer (Fig. 1a). These spectra served as direct inputs to model the thermally emitted planetary flux (F_p) from theoretical rocky exoplanets with surfaces made of each of the 15 samples. Dividing by the stellar flux (F_*) of an M-dwarf star, we obtained theoretical F_p/F_* spectra (Fig. 1b), which represent the type of data that JWST's mid-infrared instrument (MIRI) can collect. Mid-infrared wavelengths (2.5–25 µm) were selected because silicon–oxygen bond vibrations in key rock-forming minerals produce spectral features near 10 µm, and F_p/F_* ratios for airless, rocky exoplanets around M-dwarf stars peak at these wavelengths.

Longward of 8 µm, features in the laboratory emission spectra are discernible in our F_p/F_* models (Fig. 1). Our simulated JWST MIRI low-resolution spectrometer observations show that it would require about five eclipse observations to achieve the precision needed to discern features that signify high abundances of water-bearing minerals (serpentine and amphibole). Simulated broadband observations based on MIRI's photometric imaging filters show that basalts that interacted with water have flux ranges distinct from other samples. Simulated photometric fluxes even correlate with the bulk chemical composition of samples (such as the wt% Al_2O_3). Nevertheless, for these features to be visible in real observations, dozens to about a hundred eclipse measurements would be needed.

The implications

Our work shows that even among samples broadly classified as basalt, certain mineralogical features and some components of bulk chemical composition are differentiable in simulated JWST MIRI observations. As theory and observation are now aligning to suggest that many rocky exoplanet surfaces will probably be basaltic, our work implies that it might be possible to discern more geological detail than previously anticipated, potentially including mineralogical signals of past or present water.

Our study was a first look at trying to expand beyond single rock types, and we limited the variables in order to better understand the signals related to mineral and chemical characteristics. For example, our work does not consider the effects of having a regolith versus solid surface, how surface roughness might limit spectral signals, or how space weathering could alter surfaces. It would also require a lot of observation time to see some of the signatures revealed by our models. Therefore, although we cannot yet claim to detect water or specific minerals on a particular planet, our work opens the door to that possibility.

Next steps include examining more natural samples, measuring new spectra and delving into existing mid-infrared spectral databases (providing they also contain mineralogical and geochemical data). Through such efforts, we could examine how powdered samples would affect our models, what could be learned from a suite of samples that differ systematically in their hydrous mineral content, and more. Although we focused on basalt owing to its ubiquity, the mineral and geochemical differences between or within other rock types might be within reach of JWST or future observatories.

Emily C. First[1] & Esteban Gazel[2]
[1]Macalester College, Saint Paul, MN, USA.
[2]Cornell University, Ithaca, NY, USA.

This is a summary of:
First, E. C. et al. Potential for observing geological diversity from mid-infrared spectra of rocky exoplanets. *Nat. Astron*. https://doi.org/10.1038/s41550-024-02412-7 (2024).

EXPERT OPINION

“This paper presents interesting new mid-infared reflection spectra of basaltic rock samples of various composition. These types of spectra can be very interesting for characterizing rocky surfaces in and outside the Solar System. The paper is well written, the method well explained and the data in itself interesting.” **Michiel Min, SRON Netherlands Institute for Space Research, Leiden, the Netherlands.**

FIGURE

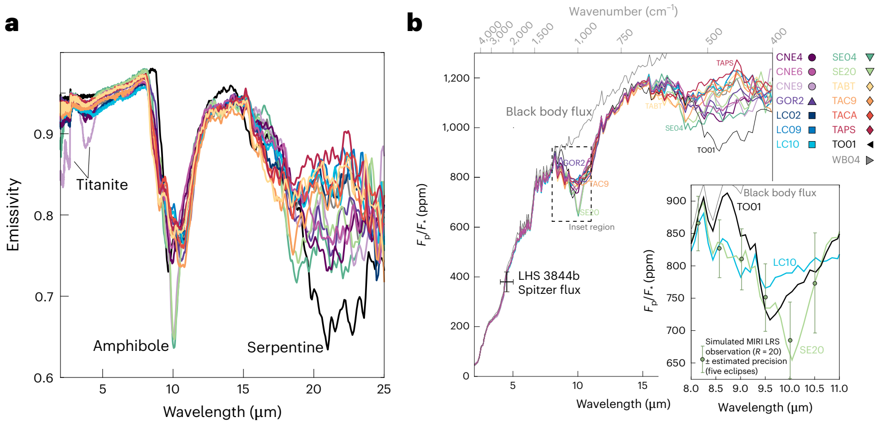

Fig. 1 | Comparison of modelled and measured emission spectra. a, The measured mid-infrared emission spectrum of each of the 15 rock samples. **b**, Theoretical planet-to-star flux ratios (F_p/F_*) for a rocky exoplanet with surface emissivity corresponding to each of the spectra in panel **a** and modelled using the properties of star LHS 3844 and its close-in rocky planet LHS 3844b. The ‘LHS 3844b Spitzer flux’ point is the mid-infrared observation of this planet, made by the Spitzer Space Telescope[2]. The inset highlights the spectra of two samples (TO01 and SE20) that show features indicative of water–rock interactions and a spectrum of a less-altered basaltic sample (LC10). In the inset, circles represent simulated JWST MIRI low-resolution spectrometer observations binned to a resolving power of 20. Error bars show the expected precision based on five eclipse observations. © 2024, First, E. C. et al.

BEHIND THE PAPER

Through this collaborative project, we learned how fun and challenging it can be to leap across fields! For example, in astronomy, ‘metal’ means elements heavier than helium, but in geology, ‘metal’ typically means elements like iron or nickel. We were driven to figure out if classifying exoplanet surfaces by general rock type was the limit of current technology, or if this wasn’t a question that had been asked yet. When we started the project, there was only one data point for the surface composition of a rocky exoplanet (LHS 3844b)[2]. But we knew how common basalt is in our Solar System, and likely beyond[4]. So, we found some basalts, and off we went! Some group members taught astronomical modelling and others explained how certain minerals form. The patience and goodwill of all involved led to a lot of learning and produced better work than we could have achieved without crossing disciplines. **E.C.F. & E.G.**

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   This work uses stellar compositions and a range of iron partitioning possibilities to calculate the bulk silicate compositions of rocky planets orbiting those stars.

FROM THE EDITOR

“Laboratory measurements are essential to the interpretation of remote sensing data of (exo)planetary surfaces, but they are still rather rare. This study directly bridges laboratory work with what we can observe with JWST and it will be a precious guide to probing the composition of bare rock exoplanets for the first time.” **Luca Maltagliati, Senior Editor, *Nature Astronomy*.**