LUNAR OBSERVATIONS FROM 5 TO 8 MICRONS WITH SOFIA AND THE SUOMI CROSS-TRACK INFRARED SOUNDER: WATER AND CHRISTIANSEN FEATURE RESULTS.

C. I. Honniball[1], M. J. Burgdorf[2], P. G. Lucey[3], T. Müller[4], Y. Chen[5], A. Arredondo[6], W. T. Reach[7], A. J. Thorpe[7] and E. R. Malaret[8]. [1]NASA Goddard Space Flight Center, Greenbelt, MD, USA (casey.i.honniball@nasa.gov). [2]University of Hamburg, Hamburg, Germany. [3]Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Mānoa, Honolulu, HI, USA. [4]Max Planck Institute for extraterrestrial physics, Garching, Germany. [5]National Oceanic and Atmospheric Administration, Silver Spring, MD, USA. [6]Southwest Research Institute, San Antonio, TX, USA. [7]Universities Space Research Association, Columbia, MD, USA. [8]Applied Coherent Technology, Herndon, VA, USA.

Introduction: In 2020 we reported observations of the Moon in the 5 to 8 µm spectral range using the Stratospheric Observatory For Infrared Astronomy (SOFIA) [1]. These observations revealed a 6 µm spectral feature attributed to molecular water at high southern lunar latitudes. At the time there were few observations of the Moon from 5 to 8 µm [2]. Since 2018 we have conducted 16 additional flights with SOFIA observing the Moon with the goals of characterizing the behavior of molecular water and searching for mineralogical signatures.

While the observations with SOFIA are unique, this spectral range is new to lunar science and the data present some challenges. Therefore, independent observations of the Moon from 5 to 8 µm are important for validating SOFIA lunar observations.

Fortunately, integrated hemispheric observations of the Moon from the Earth orbiting Cross-track Infrared Sounder (CrIS) on the Suomi National Polar-orbiting Partnership Satellite are newly available that can be used to validate SOFIA lunar observations. In this abstract we compare lunar spectral shapes observed by SOFIA and CrIS from 5 to 8 µm.

Observations: The CrIS lunar observations presented here were acquired on January 27th, 2018 at 21:55 UT. The lunar phase angle of the observations were 49.9˚ and the subsolar longitude and latitude was 46.6˚E and 0.2˚N, respectively. The CrIS measurements are disk integrated and therefore includes all lunar temperatures but is dominated by the warmest temperatures [3].

SOFIA observations, on the other hand, are spatially resolved at the 2 to 4 km scale. To compare CrIS and SOFIA observations we selected a SOFIA observation from May 12th, 2022 flight F0868 near the subsolar point within Mare Fecunditatis with nearly the same subsolar longitude and latitude as when the CrIS data were acquired (45.2˚E and 0.07˚S).

We typically use Mare Fecunditatis as a reference to remove an artifact in SOFIA FORCAST data [1]; for this comparison we instead use an observation of mare near Copernicus crater as the reference.

SOFIA vs. CrIS: Figure 1 shows the spectral shapes of SOFIA in black and blue and CrIS in green. The black SOFIA spectrum is before the reference is removed while the blue spectrum is with the reference removed. Comparison of the spectral shapes is most easily seen in Figure 1 between the blue spectrum of SOFIA and the green spectrum of CrIS. The shape of the spectra are similar and for the first time we have independent confirmation of the basic spectral character of the SOFIA observations. The shapes are not identical though, with slight deviations near the ends of the spectra that may be due to the fact that each spectrum contains very different distributions of surface temperatures.

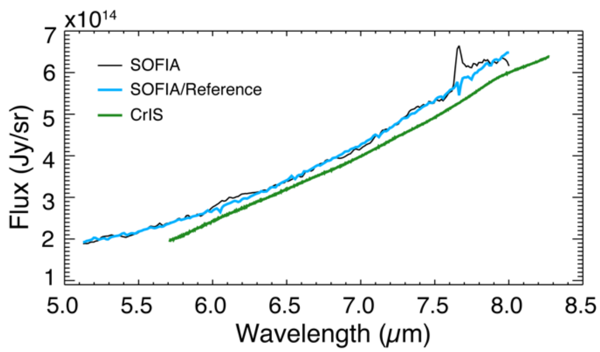

Figure 1: *Spectral shape comparison of SOFIA in black before the reference is removed, SOFIA in blue after the reference is removed, and CrIS in green.*

Figure 2 shows the spectra from Figure 1 normalized to a continuum, revealing spectral features. For the continuum, we used a 2nd order polynomial fit below 5.9 µm and from 6.5 to 7.5 µm, avoiding the 6 µm region so that any water feature does not influence the fit and avoiding the residual atmospheric methane band beyond 7 µm in SOFIA measurements.

When looking at the spectral shapes in Figure 2 we see that the 6 µm region in CrIS has a broad spectral hump whereas SOFIA does not. In the SOFIA measurements before the reference in black we see an apparent band near 6 µm that is caused by imperfect atmospheric correction and instrumental artifacts. In the SOFIA observations with the lunar reference removed these artifacts are removed. In both cases, we do not see a broad hump like in CrIS. We do not believe this broad feature is the 6 µm water feature due to its breadth and is instead part of the continuum of the Moon due to as yet unidentified processes.

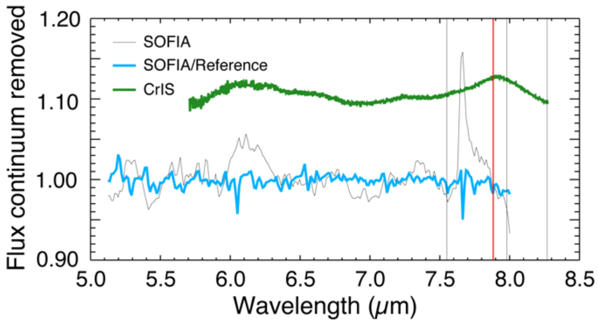

Figure 2: *Spectral comparison of continuum removed SOFIA flux before reference in black, after reference in blue and CrIS in green offset form unity. A 2nd order polynimial is used to define the continuum. This view of the spectra reveal potential water or minerological spectral features. The vertical black lines show the wavelengths selected for CrIS to predict the CF peak and the red line is the predicted peak at 7.88 µm.*

6 µm water feature: The recent report of a 6 µm band on the lunar surface by SOFIA [1,4] showed that this spectral range contains information on the presence of water. In Figure 2, the SOFIA spectrum in black contains a an apparent 6 µm band as explained previously while the reference removed SOFIA spectrum in blue does not show a 6 µm water feature. This is due to both Mare Fecunditatis and the reference near Copernicus having the same amount of water so when we ratio the two to remove the artifact any 6 µm feature is also removed.

In the CrIS measurements there is also no clear evidence of a 6 µm water feature. This is likely due to the disk integrated observation.

Christiansen Feature (CF): A Christiansen Feature has been detected and characterized by the Diviner Radiometer Experiment (Diviner) on the Lunar Reconnaissance Orbiter (LRO) using 3 narrow band channels with wavelength ranges of 7.55-8.05, 8.1-8.4, and 8.38-8.68 µm [5]. The CF contains information on the average silicate mineralogy of lunar regions. CrIS data provides high resolution spectra measurements of the lunar CF across the nearside of the Moon, weighted by the surface temperature.

The CrIS data show a clear CF at ~7.9 µm, indicating a felspathic mineralogy by direct comparison with laboratory data. Most of the signal at the time of observation came from within 30 degrees of latitude and longitude of the subsolar point where majority of the signal originated from mare surfaces. We predict the CF peak should be at 8.2 µm by projecting Diviner CF measurements to the CrIS subsolar longitude and latitude, and weighting the data by 8 µm spectral radiance [5]. We also tested the parabolic approach used for Diviner [5] to predict the CF peak position on 3 wavelengths in the CrIS measurements (7.55, 7.98, 8.27 µm; Figure 2 vertical lines). The predicted band is 7.88 µm and indicates the mis-match between CrIS and Diviner is not due to errors in the 3-wavelength parabolic estimate of CF wavelengths.

SOFIA observations do not show a clear CF due to contamination by an atmospheric methane band that we have not yet been able to correct in our atmospheric calibrations in the data before the reference is removed (black). Furthermore, based on CrIS results, the SOFIA data only capture the short wavelength portion of the band, so a maximum may not be captured.

Discussion: Results from LRO Diviner and CrIS are somewhat inconsistent with respect to the Christiansen Feature. Diviner data generally indicate a peak position somewhat past 8 µm in highland terrains, and significantly longer in mare terrains. In CrIS data, the hemispheric peak, weighted somewhat toward mare terrains owing to the solar longitude are clearly shortward of 8 µm. However, we note that the position of the peak could also be affected by the observing conditions as the Moon only fills part of the field of view of CrIS.

BepiColombo performed two fly-bys of the Moon observing the Moon with the MErcury Radiometer and Thermal Infrared Spectrometer (MERTIS) instrument from 7-14 µm [6-8]. MERTIS observations revealed instead a minimum around 8 µm and no strong CF [6-8]. The observing conditions for MERTIS provided 500 km/px lunar coverage of mostly the nearside. The discrepancy between the CrIS, MERTIS, and Diviner observations will need to be investigated further.

Conclusions: The observations from CrIS have provided an independent measurement of lunar spectral shapes from 5 to 8 µm that are consistent with SOFIA measurements. There are some differences in the spectral shapes, mainly the wide hump around 6 µm that remain unexplained.

The disagreement in the presence of a CF in CrIS, MERTIS, and Diviner observations will need further investigation and more independent measurements.

References: [1] Honniball C.I. et al., (2020) *Nat Ast*., 10.1038/s41550-020-01222-x. [2] Salisbury J.W. et al., (1995) *Icarus.* [3] Müller T.G. et al., (2021) *A&A*., 10.1051/0004-6361/202039946. [4] Honniball C.I. et al., (2022) *GRL*, 10.1029/2022gl097786. [5] Greenhagen B.T. et al., (2010) *Sci*., 10.1126/science.1192196. [6] Hiesinger H. et al., (2021), #1494, 52nd LPSC. [7] Maturilli A. et al., (2021), #2085, 52nd LPSC. [8] Wohlfarth K. et al., (2021), #1241, 52nd LPSC.