POTENTIAL OF METEOROLOGICAL SATELLITES AS SPACE TELESCOPES: LUNAR INFRARED SPECTRUM OBSERVED BY HIMAWARI-8. G. Nishiyama[1](gaku.nishiyama@eps.s.u-tokyo.ac.jp), N. Namiki[2,3], S. Sugita[1,4], and S. Uno[5], [1] Department of Earth and Planetary Science, The University of Tokyo, [2] National Astronomical Observatory of Japan, [3] The Graduate University for Advanced Studies, SOKENDAI, [4] Research Center of the Early Universe, The University of Tokyo, [5] Department of Astronomy, The University of Tokyo.

Introduction: The images taken by the Japanese meteorological satellite Himawari-8 have not been used for astronomical or planetary research until recently. Himawari-8 takes high-resolution pictures of the global weather by scanning the earth from east to west every 10 minutes. Simultaneously, its images cover space surrounding the earth. Namely, stars, planets, and the moon have been imaged many times since the start of the Himawari-8 operation in 2015 (Figure 1), which enables to draw light curves of dying stars such as Betelgeuse [1].

The variety of bands covering wavelength from visible to mid-infrared wavelength is another significant characteristic of Himawari-8. Especially, Himawari-8 has 9 bands within 6 – 14 μm. Such many bands have not been used for spaceborne observations of the moon in this wavelength range. For example, Diviner Radiometer onboard Lunar Reconnaissance Orbiter (LRO) has four bands over 7.5 – 23 μm. Thus, the mid-infrared images taken by Himawari-8 are unique and potentially valuable for planetary science.

In particular, the mid-infrared spectrum of airless bodies is of importance in understanding their thermophysical condition and composition. For example, the lunar surface temperature is a key to constrain the surficial mm-scale roughness, thermal inertia, and rock abundance [2,3,4]. Moreover, the thermal emission peak of H_2O around 6 μm was discovered recently on the moon for the first time[5], indicating the significance of a thorough investigation of the lunar surface in this band.

Thus, the Himawari-8 data could be utilized for planetary science. However, it has never been examined yet. Below, we develop the procedure to retrieve the lunar infrared spectrum from Himawari-8 images and to compare it with the Diviner measurement. Then, we constrain the lunar physical conditions by comparing Himawari-8 data with thermal simulations.

Method: To derive the lunar brightness temperature, we use the Himawari Standard Data (HSD) which has been published by the Japan Meteorological Agency since 2015. The infrared HSD is well-calibrated with a temperature-controlled blackbody inside the imager every 10 minutes. From all the HSDs taken by the end of November 2021, we manually extract 248 lunar images which cover more than half of the moon in the scanned space. Then, we determine the lunar center in each image by fitting a circle to the lunar rim pixels, so that the HSD pixels can be linked to the longitudes and latitudes on the moon with SPICE. The brightness temperature of every HSD pixel is calculated from the radiance values for each band, assuming the emissivity of 0.95.

The background noise from the earth and the dayside of the moon is estimated from the non-zero radiance of space. In HSD, the earth and the moon have a dim halo around them, likely because of multiple scattering of light within the optical system. The noise level is evaluated from the radiance of the halo as a function of distance from the edge of bright pixels.

First, to interpret the brightness temperatures of the nightside, we simulate the daily variation of the surface temperature of rock and regolith. Using the 1-D thermal conductive models with thermal properties of rock and regolith based on Apollo samples [3,6], we calculate the temperature of the mixture of rock and regolith for every latitude and local time.

Next, we evaluate the dayside temperatures by taking roughness into consideration for the comparison with the lunar morning and evening. We simulate the surface regolith temperature of a facet with various slope angles and azimuths at each lunar latitude and local time. Then, we integrate the radiance of terrain with roughness parameterized with a Hapke mean slope angle, incorporating km-scale topography. Here we use a statistical model among incidence angle, emission angle, shadow ratio, and roughness [7,8].

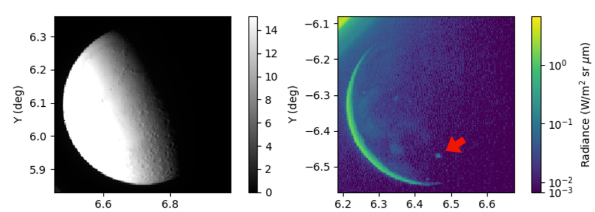

Figure 1. The moon in HSD at band 13 (10.19 – 10.61 μm). The left and the right image is taken in 2018/12/28 08:20 and 2015/11/09 13:10 in UTC, respectively. The red arrow in the right figure indicates Tycho crater. Note that the color bar of the right image is log-scaled.

Result: The lunar brightness temperature in HSD is consistent with the temperature measured by Diviner. Figure 2 shows lunar equatorial brightness temperature measured by Himawari-8 and Diviner. Although the

HSD count is saturated in most daytime, brightness temperatures match well in the morning and evening. Contract to dayside values, the error is large in nightside due to the low level of signals. However, at some bright areas such as Tycho crater in nightside (Figure 1), HSD matches the Diviner data within a standard deviation, indicating the consistency between HSD and Diviner.

The HSD brightness temperatures are different among various bands. In the morning and evening, the brightness temperature is higher at band 11 (8.40 – 8.78 μm) than band 15 (11.90 – 12.86 μm) by tens of K. Besides, the difference rises from noon to the sunrise in the morning and the sunset in the evening. At nightside, such anisothermalities among various bands are also recognized. Around midnight, Tycho crater has the maximum brightness temperature difference of 15 K among various bands (Figure 3). These anisothermalities are qualitatively consistent with Diviner measurement and possibly indicate wide-ranging temperature variations within a field of view [2].

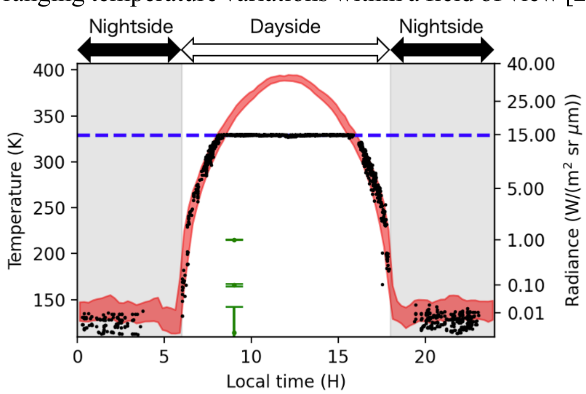

Figure 2. Comparison of equatorial temperature around 8.5 μm measured by Himawari-8 with the one by Diviner. The red area shows a standard deviation range of Diviner Global Cumulative Product at channel 5 (8.38 – 8.68 μm). The black points are Himawari-8 data at band 11 (8.40 – 8.78 μm). Note that HSD is saturated at the blue dashed line. Each green bar indicates the HSD errors at the radiance of 0.01, 0.1, 1 W/m^2/sr/μm.

Discussion: The anisothermality in the morning and evening can be interpreted as an effect of surficial roughness. Unlike flat terrain, the slope distribution on rough terrain results in a wide spatial variation of temperature in a field of view, causing different brightness temperatures at different wavelengths due to the nonlinear relationship between temperature and radiance. Comparison between HSD and rough-terrain models shows that values of radiance simulated with a Hapke mean slope angle of 15 degrees show good agreement with those of HSD as long as the incident angle is smaller than 70 degrees. The difference between HSD and simulation is smaller than 10 %. At the Apollo landing sites, the mean slope of cm-scaled roughness ranges from 6 to 24 degrees [9], so the mean slope of 15 degrees is consistent with the lunar surface observed locally by Apollo missions.

The nightside anisothermality at Tycho crater likely reflects the rock abundance higher than the lunar average. Based on the thermal inertia of the Apollo samples, the temperature of the rock is higher than that of the surrounding regolith in the lunar nightside [4]. As a result, a mixture of rock and regolith causes anisothermalities similar to the roughness effect in the morning and evening. Comparison between multi-band observation and temperature of a mixture of rock and regolith shows that the trend among 9-bands brightness temperatures of infrared HSD is consistent with the mixing ratio of rock from 3.6 to 10.5 % (Figure 3). This range is consistent with Diviner measurement [4].

As shown above, HSD is totally consistent with Diviner data and has a sufficiently high quality for planetary science. Although the spatial resolution is lower than Diviner, the HSD has more bands in mid-infrared wavelength than any other onboard instruments. Therefore, HSD is not only useful for cross-calibration but can provide a new and valuable data source for planetary science.

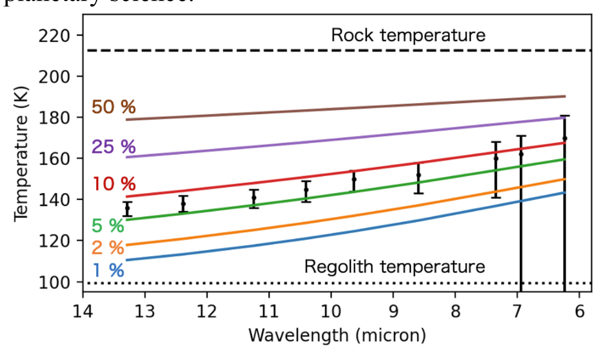

Figure 3. Brightness temperatures of Tycho crater at the local time of 1.97 H. The black points are the HSD brightness temperatures at 2015/09/16 17:00. The black dashed and dotted lines are the temperatures of rock and regolith, respectively. The solid lines show mixture models with rock ratios of 1, 2, 5, 10, 25, and 50 %.

References: [1] Taniguchi D et al. submitted to *Nat. Astron*. [2] Bandfield J. L. et al. (2015) *Icarus*, 248, 357-372. [3] Hayne P. O. (2017) *J. Geophys. Res: Planets*, 122, 2371–2400. [4] Bandfield J. L. et al. (2011) *J. Geophys. Res: Planets*, 116, E00H02. [5] Honnibal C. I. et al. (2020) *Nat. Astron.*, 5, 121–127. [6] Vasavada A. R. et al. (1999) *Icarus*, *141*, 179-193. [7] Hapke B. (1984) *Icarus*, *59*, 41-59. [8] Smith B. G. et al. (1967) *J. Geophys. Res: Planets*, 72, 4059-4067. [9] Helfenstain P. and Shepard M. K. (1999) *Icarus*, 141, 107-131.