1. Introduction

The Moon's optical characteristics are its most accessible properties, which have been long studied. Our eyes sense the Moon at wavelengths in the visible spectrum (0.38–0.76 μm). By using instruments, the knowledge of the Moon's spectral properties has expanded to include the near-infrared (NIR: 0.76–1.4 μm) (Buratti et al., 1996; Ohtake et al., 2010; Robinson & Riner, 2005), short-wavelength infrared (1.4–3.0 μm) (Kieffer & Stone, 2005; Kouyama et al., 2016; McCord et al., 1981; Pieters et al., 2009; Shkuratov et al., 2011; Stone et al., 2002; Velikodsky et al., 2011; Wu et al., 2018), and the long-wavelength infrared (LWIR: 5–1,000 μm) (Donaldson Hanna et al., 2017; Hayne et al., 2017; Lawson et al., 2000; Nash et al., 2017; Paige et al., 2010; Pettit & Nicholson, 1930; Saari et al., 1972; Vasavada et al., 2012; Williams et al., 2017). Despite some research at low-spatial resolution (Clark, 2009; Sunshine et al., 2009), many of the Moon's characteristics in the mid-infrared (MIR: 3–5 μm) remain to be discovered. What does the Moon look like at MIR wavelengths (3–5 μm)? How does it change with the lunar phase? What is the essence behind its appearance? Observations with higher spatial resolution are necessary to reveal the Moon’s properties in this range of wavelengths.

In this paper, we show the MIR Moon's appearance and its variation with lunar phase observed by China's high-resolution geostationary satellite, Gaofen-4 (GF-4), and reveal the essence behind its appearance. The paper is organized as follows: in Section 2, we introduce the observation and data; in Section 3, we present...
our results, including the appearance of the MIR Moon and the detailed temperature variation of the lunar disk; Section 4 is a discussion of our findings, including the separation of the reflected and emitted radiations, and distribution characteristic of temperature over the lunar disk; and Section 5 is our summary.

2. Data

At 00:04 Beijing time on December 29, 2015, GF-4 was launched from the Xichang Satellite Launch Center using a Long March 3B rocket. GF-4 is a geostationary satellite, part of the China High-resolution Earth Observation System. The task of GF-4 is to offer visible and near-infrared (VNIR) spatial resolution of better than 50 m and MIR spatial resolution of 400 m from geostationary orbit. GF-4 has a large-array VNIR detector and an MIR detector with fields of view of 0.8° × 0.8° and 0.66° × 0.66°, respectively, and instantaneous fields of view of 1.363 and of 11.249 μrad/pix, respectively. Based on the large-array detectors, the entire lunar disk was imaged in both VNIR and MIR in a single exposure with spatial resolutions of up to ~500 m/pixel and ~4 km/pixel, respectively. Such high-resolution single-exposure imaging of the whole lunar disk allows us to capture the brightness/temperature distribution across the lunar disk.

GF-4 first imaged the Moon in the MIR on the day of China’s Lantern Festival (March 2, 2018). Then, before and after the day of the century’s longest lunar eclipse (July 28, 2018), four observations were taken with phase angles of approximately ±30°, 90° (half Moon), and 0° (full Moon). For each imaging of the Moon, we observed in the VNIR (bands 1–5) and the MIR (band 6). The spectral range of band 6 is 3.50–4.10 μm with the lunar effective wavelength, defined by Equation 1 in Kieffer and Stone (2005), from 3.77 μm in term of only considering the reflected sunlight to 3.82 μm with the lunar temperature of 390 K. This wavelength marks the turning point at which the reflectance of lunar soil starts to decrease: according to laboratory spectra of lunar soils, the wavelength at which lunar soil has the largest reflectance is around 3.8–4.0 μm (Salisbury et al., 1997). Hence, the GF-4 provides an excellent opportunity to show in detail the combined effects of reflected sunlight and thermal emission of the Moon. Tables S1 and S2 in the supporting information provide details about the instrument performances and the measurement geometry. Text S1 provides details about the calibration and temperature calculation.

3. Results

3.1. The MIR Moon’s Appearance and Variation With Lunar Phase

Figure 1 shows the Moon in the NIR and MIR range imaged by GF-4 over 3 days. The images of March 2 and August 4 are not shown because they were uncalibrated. (The images of all the 5 days are shown in Figures S1 and S2 in the supporting information.) The NIR lunar images are similar to visible images, indicating that both are dominated by solar reflection. The Moon in the MIR is largely different from the Moon in the VNIR. At first glance, the Moon in MIR exhibits limb darkening while the Moon in the VNIR shows a relatively uniform brightness (Lommel–Seeliger behavior). Moreover, their brightness appear inverted. On the MIR lunar disk, the low-albedo surfaces, such as maria, become brighter than the highlands, and the high-albedo features, such as fresh craters, crater rays, and the Reiner Gamma swirl, become darker than their surroundings. The Moon in the MIR shows a diminished contrast between maria and highlands, and fresh and mature materials are not as sharp as those in the VNIR Moon. Crater rays appear dimmer than those in the VNIR Moon. At full Moon (July 28) in the VNIR, the darkest maria region (5.53°N, 9.2°W) has 24.93 W/m²/str/μm radiance while the brightest region, Aristarchus, has 102.11 W/m²/str/μm radiance. In the MIR, the darkest maria radiance is 9.42 W/m²/str/μm and Aristarchus has a radiance of 5.62 W/m²/str/μm. Their contrast is largely inversed from 4.1 (VNIR) to 0.6 (MIR). In contrast, topographies such as craters, domes, wrinkle ridges, and Mons are obvious even near zero phase angle. The MIR images of the full Moon show that the highlands are covered with numerous craters, which are not obvious in the VNIR images.

These features indicate that at MIR wavelengths the Moon includes both the reflected sunlight and the thermal emission. The obvious topographies, limb darkening, and inverted brightness compared to the VNIR Moon indicate the thermal emission. The diminished contrast between maria and highlands and dimmer crater rays indicate the combination of the thermal emission and solar reflection. The higher the albedo of the surface, the lower its thermal emission: thus, the combination of these two opposing effects causes the reduced contrast in the MIR.
The brightness distribution of the Moon in the MIR changes with the local time. The brightest location follows the Sun and is not exactly at the subsolar point but in the nearby mare. The visibility of crater rays also varies with the solar angle. The closer to the subsolar point they are, the clearer they become. The clearest crater ray system in the VNIR, Tycho, is almost invisible in the MIR because it is far from the equator. The obvious crater ray systems in the MIR are those at low latitudes, and the two most obvious craters are Copernicus and Kepler. As shown in the MIR images of July 25 and August 4, when the subsolar point is far from the two craters, the crater rays are invisible. This indicates that in the MIR, the proportion of thermal emission decreases and the proportion of surface reflection increases as one moves away from the subsolar point. Mare Tranquillitatis has a lower albedo than Mare Serenitatis. Hence, Mare Tranquillitatis is brighter than Mare Serenitatis even for a solar incidence angle \( i = 45^\circ \) (MIR image of July 28). Mare Tranquillitatis becomes darker than Mare Serenitatis when the solar incidence angle is \( i = 60^\circ \) (MIR image of July 30). The ratio of the average radiance between Mare Tranquillitatis and Mare Serenitatis for July 25, 28, and 30 is 1.28, 1.07, and 0.85, respectively. This means that for the Moon in the MIR, both the absolute brightness distribution and the relative brightness among regions vary with local time within one lunar day, demonstrating the effect of the solar insolation.

### 3.2. Temperature Map of the Whole Lunar Disk

Figure 2 shows the brightness temperature maps. As with the image in the MIR, the brightness temperature image also clearly shows the topography. The brightness temperature is approximately concentrically...
distributed around the subsolar point. For identical solar angles, the low-albedo region has a higher temperature than the high-albedo region. The temperature difference between maria and highlands for the same solar angle is larger at high incidence angle and decreases with the increasing incidence angle. The location of the highest temperature is not exactly at the subsolar point but in the nearby mare, because in the examples we show, the subsolar point is always located at a short distance from a mare. The highest brightness temperatures of the 3 days are $384 \pm 1.1$, $386 \pm 1.1$, and $385 \pm 1.1$ K with radiometric calibration uncertainty of $\pm 2.25\%$ (1σ standard deviation). The region that has the highest temperature is almost the same as that of the highest radiance of the Moon in the MIR. This indicates that around noon, the thermal emission dominates the lunar brightness in the MIR. The basalts with the lowest albedo have a higher temperature than most highlands, even at a 45° solar incidence angle. This indicates that all three types of lunar disk images (VNIR, MIR, and brightness temperature) are controlled by albedo.

Figure 3 shows the histogram of all three types of lunar image. The absolute brightness of Moon in the NIR is much higher than in the MIR. At full Moon, the highest brightness in the NIR can be as high as 90 W/m²/Sr/μm while in the MIR it is less than 9 W/m²/Sr/μm. The brightness in the NIR depends on the lunar phase while the brightness in the MIR was relatively stable over the 3 days with the highest brightness <9 W/m²/Sr/μm. For the brightness temperature, all phases exhibit a negatively skewed distribution and the highest values are also similar. At full Moon, the VNIR band exhibits a bimodal distribution which corresponds to the maria and highlands, while the MIR band exhibits an approximately uniform distribution, reflecting the diminished contrast between maria and highlands. The histogram of the –30° phase (waxing phase of July 25) in the VNIR is similar to that of full Moon, while that of 30° phase (waning phase of July 30) is quite

**Figure 2.** Brightness temperature distribution of the Moon disk. “+” represent subsolar and “×” represent subcamera points. Dashed lines represent solar incidence angles with an interval of 15°.
different with a positively skewed distribution. This reflects the fact that the lunar western hemisphere has more maria than its eastern hemisphere.

4. Discussion

4.1. Separation of the Reflected and Emitted Radiations

The fundamental vibration bands of life-related molecules such as water and organic matter occur at MIR wavelengths, so that the separation of the reflected sunlight from the thermal emission is conducive to the research of these materials. The simultaneous imaging of all six bands allowed for a direct comparison between the Moon in the VNIR and MIR and the separation of the reflection and thermal emission from the Moon in the MIR. Figure 4 shows the contribution of the reflective and emissive lunar radiance. At 3.77 μm for most of the Moon, the thermal emission is greater than the reflected solar radiance. The emitted fraction of the maximum temperature area over the 3 days is $84.7 \pm 0.25\%$. The thermal emission varies considerably from 0 to 8 W/m²/Str/μm, whereas the reflected fraction usually varies between 1 and 2 W/m²/Str/μm, which causes both types of radiance to be visually unrelated. However, the right side of the scatter plot shows a
fan-like shape with a pointed tip on the extreme right: the high-albedo side of the envelope indicates a negative correlation, showing that a larger thermal emitted radiance corresponds to a smaller reflected radiance.

4.2. Distribution of Temperature Over the Disk

Since the early twentieth century, many efforts have been made to investigate the temperature variation across the lunar disk. The commonly suggested model to represent the local temperature $T$ variation with solar incidence angle $i$ was in the form

$$T = T_{SS} \cos^{b}(i)$$

where $T_{SS}$ is the temperature of the subsolar point and $b$ is a parameter to be fit. For a Lambert sphere, $b$ is 1/4. Pettit and Nicholson (1930) found that the center-to-limb temperature variation as a function of the local solar incidence angle $i$ was $\cos^{1/6} i$ rather than the $\cos^{1/4} i$ variation expected for a Lambertian surface. Conversely, using the Clementine LWIR camera images, Lawson et al. (2000) found that the Lambertian temperature model is a fair approximation for nadir-looking temperatures, which is supported by Diviner (Williams et al., 2017). Based on 23 scans of the sunlit portion of the surface through a lunation, Saari et al. (1972) suggested a replacement of the $\cos^{1/6} i$ law by an expression which is linear in $\cos i$. Note that none of previous studies imaged the entire lunar disk with a single exposure.

The high-resolution multiband images of GF-4 taken as single exposures provide a good opportunity to illuminate in detail the center-to-limb variability for both reflection and temperature. Figure 5 shows the radiance and brightness temperature as a function of local solar incidence angle. To avoid the effects of compositional variation, the profiles were carefully selected from compositionally homogeneous regions for both highlands and maria. The profile across the lunar surface of the Moon in the MIR is smoother than that of the Moon in the VNIR, which is consistent with the diminished contrast of the Moon in MIR. The larger minimum–maximum variation in the highlands in both VNIR and MIR bands compared to maria indicates a greater roughness of the highlands. The profiles confirm relatively uniform brightness across the lunar disk for the VNIR range and limb darkening for both the MIR range and brightness temperature. But neither of the two types of lunar limb darkening obeys the Lambertian model. For the MIR band, the

**Figure 4.** Reflective and emissive lunar radiance.
Figure 5. Radiance and brightness temperature versus local incidence angle. Left column: Maria. Right column: Highlands. Top: band 5. Middle: band 6. Bottom: brightness temperature.
relationship between radiance and solar incidence angle is linear with a slope of $-0.07$ W/m$^2$/Sr/μm/deg for the highlands and $-0.1$ W/m$^2$/Sr/μm/deg for the maria.

For brightness temperature, all profiles show less limb darkening compared to the Lambertian model. The previously suggested model, Equation 1, does not adequately fit for wide range of solar incidence angle. We suggested an equation of the form:

$$ T = aT_{SS}\cos^{1/4}(i) + (1 - a)T_{SS}\cos^{b}(i) $$

(2)

where $a$ and $b$ are parameters to be determined. The model is a combination of the Lambertian function and non-Lambertian function. The former describes that the brightness temperature variation as a function of solar incidence angle is approximate Lambertian model at smaller incidence angle, while the latter describes the deviation of the brightness temperature from the Lambertian model at larger solar incidence angle. The fitted values for $a$ and $b$ are shown in Table S3 and the fitted lines are shown in Figure 5(e) and 5(f). It can be seen that all data are well fitted by Equation 2. To compare with previous results, the fitted results using model 1 is also shown. Note that the profile for maria for the full Moon varies more linearly as $T = 319.72 + 58.62\cos i$. One of the reasons might be the difficulty in selecting compositionally homogeneous mare regions. The fitted $b$ for Equation 1 is approximately traditional $\cos^{1/6}i$. Our results indicate that the decrease of the brightness temperature when moving away from the subsolar point is slower than would be described using a Lambertian model, and the larger the solar incidence angle, the slower the temperature decrease. This is due to topographic effects: at large solar incidence angle, the sunward facing slopes enhanced thermal emission compared to a flat surface. The topographic effects become stronger as the solar incidence angle increases. Figure 5 shows that at solar incidence angle $>60^\circ$ at full Moon, the average topography should be tilted toward the Sun by angles of $\sim10^\circ$ relative to a horizontal surface.

Lawson and Jakosky (2001) found that as the phase angle increases the influence of surface roughness grows. However, the emission angle of Clementine is $0^\circ$ and the phase angle is equal to the solar incidence angle. That is, the influence of the surface roughness as a function of phase angle derived from Clementine data is actually the solar incidence angle. The large variations of both solar incidence angle and emission angle across the whole lunar disk derived from GF-4 observations better illuminate the effects of surface roughness as a function of various geometries. Figure 5 shows that for both maria and highlands the temperature profile as a function of solar incidence angle at full Moon deviates more from the Lambertian model than that at large lunar phase, suggesting that the influence of surface roughness is stronger at small lunar phase rather than at large lunar phase. This is understandable. Compared to large lunar phase, observations at full Moon have less shadow within the field of view and hence more enhanced thermal emission. In summary, solar incidence angle dominates the thermal emission, but phase angle also has an influence.

5. Summary

The Moon in the MIR exhibits many interesting phenomena which were previously unknown. It contains abundant information about lunar reflection and thermal emission. The GF-4 high-resolution observations of the entire lunar disk in a single exposure offer a unique thermal emission perspective of the lunar hemisphere, and the data illuminate global temperature variations with local incidence and emission angles that are not available to lunar-orbiting spacecrafts and not restricted by the terrestrial atmosphere. When compared to the previous models on thermal spatial variability, the high-resolution MIR lunar images together with the simultaneously imaged VNIR Moon directly illustrate it. Both the reflectance and emissivity are strongly dependent on the illumination and observation geometry. The high-spatial resolution observations of the whole lunar disk provide an unprecedented opportunity for future work building a directional distribution model for both reflectance and emissivity. Moreover, more knowledge on lunar reflection and thermal emission, such as surface roughness and thermal inertia, can be derived by future long-term data analysis.

Data Availability Statement

The raw data, the retrieved brightness temperature, and the separated reflective and emissive radiance are available at https://zenodo.org/record/3758791#.Xp5kvsgzaUk. These data can be read with software ENVI.
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