MODELING THE INFRARED SPECTRUM OF THE EARTH–MOON SYSTEM: IMPLICATIONS FOR THE DETECTION AND CHARACTERIZATION OF EARTHLIKE EXTRASOLAR PLANETS AND THEIR MOONLIKE COMPANIONS

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ABSTRACT

The Moon maintains large surface temperatures on its illuminated hemisphere and can contribute significant amounts of flux to spatially unresolved thermal infrared (IR) observations of the Earth–Moon system, especially at wavelengths where Earth’s atmosphere is absorbing. In this paper we investigate the effects of an unresolved companion on IR observations of Earthlike exoplanets. For an extrasolar twin Earth–Moon system observed at full phase at IR wavelengths, the Moon consistently comprises about 20% of the total signal, approaches 30% of the signal in the 9.6 μm ozone band and the 15 μm carbon dioxide band, makes up as much as 80% of the signal in the 6.3 μm water band, and more than 90% of the signal in the 4.3 μm carbon dioxide band. These excesses translate to inferred brightness temperatures for Earth that are too large by 20–40 K and demonstrate that the presence of undetected satellites can have significant impacts on the spectroscopic characterization of exoplanets. The thermal flux contribution from an airless companion depends strongly on phase, implying that observations of exoplanets should be taken when the star–planet–observer angle (i.e., phase angle) is as large as feasibly possible if contributions from companions are to be minimized. We show that, by differencing IR observations of an Earth twin with a companion taken at both gibbous and crescent phases, Moonlike satellites may be detectable by future exoplanet characterization missions for a wide range of system inclinations.

Key words: astrobiology – Earth – infrared: planetary systems – Moon – planets and satellites: detection – techniques: miscellaneous

1. INTRODUCTION

The Moon has played a crucial role in maintaining the long-term stability of Earth’s obliquity and, thus, climate (Laskar et al. 1993), although the presence of a large satellite does not always guarantee such stability (Ward et al. 2002). Furthermore, simulations indicate that the Moon-forming impact (Hartmann et al. 1986) could have driven away a significant mass of volatiles, such as water, from the proto-Earth (Genda & Abe 2005). Thus, the presence of a large moon has important consequences for the characterization and understanding of terrestrial extrasolar planets.

Planet formation simulations show that giant impacts like the Moon-forming impact may be common (Ida et al. 1997; Canup 2004; Elser et al. 2011). Consequently, moons are likely to contribute to observations of exoplanets, and these satellites are likely to be unresolved from their host. For example, the angular separation of the Earth and Moon at a distance of 5 pc is smaller than 0.5 mas, which is below the angular resolution of future exoplanet characterization missions (Beichman et al. 1999, 2006; Cash 2006; Traub et al. 2006; Cockell et al. 2009). Recent near-infrared (near-IR) observations of the Earth–Moon system from NASA’s EPOXI mission (Livengood et al. 2011) demonstrated that the Moon can contribute a significant amount of the combined flux at wavelengths where Earth’s atmosphere is strongly absorbing, an effect mentioned in Des Marais et al. (2002). Thus, an exomoon can affect our understanding of its host, be it through clarification or obfuscation, making it prudent to investigate how the presence of an exomoon may be detected or inferred, and how the presence of an undetected moon could confound observations of terrestrial exoplanets.

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the nondetection of a satellite can lead to the mischaracterization of the host planet’s obliquity, orbital longitude of vernal equinox relative to inferior conjunction, and thermal properties. However, direct IR observations of exoplanets will likely be spectrally resolved, not bolometric. Thus, it is important to investigate how the addition of spectral resolution will change these conclusions.

In this paper we use spectrally resolved models to determine the significance of the Moon’s contribution to spatially unresolved IR observations of the Earth–Moon system, and the extent to which a Moon twin (or exoMoon) may influence spectroscopic characterization of an Earth twin (or exoEarth). We investigate how the thermal flux from an airless world similar to the Moon in all ways except size (i.e., a Moonlike world), and its phase dependence, can be used to detect moons orbiting Earthlike exoplanets. Finally, we discuss the implications of our findings for future exoplanet detection and characterization missions.

2. MODEL DESCRIPTION

Our models of the disk-integrated spectra of Earth and a Moonlike world compute the integral of the projected area-weighted intensity in the direction of the observer, which can be written as

\[ F_\lambda (\hat{n}, \hat{s}) = \frac{R^2}{d^2} \int I_\lambda (\hat{n}, \hat{o}, \hat{s})(\hat{n} \cdot \hat{o}) \, d\omega, \]  

(1)

where \( F_\lambda \) is the disk-integrated specific flux density received from a world of radius \( R \) at a distance \( d \) from the observer, \( I_\lambda \) is the location-dependent specific intensity in the direction of the observer, \( \hat{n} \) is a surface normal unit vector, \( \hat{o} \) and \( \hat{s} \) are unit vectors in the direction of the observer and Sun (or host star), respectively, and \( d\omega \) is an infinitesimally small solid angle of the globe. The integral in Equation (1) is over the entire observable hemisphere \((2\pi \, \text{sr})\) and the dot product at the end of the expression ensures that an element of area \( R^2 \, d\omega \) near the limb is weighted less than an element of equal size near the sub-observer point. Note that, for reflected light, \( I_\lambda \) will be zero at locations on the nightside of the world (i.e., where \( \hat{n} \cdot \hat{s} < 0 \)), but is non-zero at all locations when considering thermal emission. The following subsections describe our techniques for solving Equation (1) for Earth and a Moonlike companion.

2.1. Earth Model

To simulate Earth’s appearance to a distant observer, we use the NASA Astrobiology Institute’s Virtual Planetary Laboratory three-dimensional spectral Earth model, which generates temporally and spectrally resolved disk-integrated synthetic observations of Earth. This model has been described and extensively validated, both for temporal variability and for a variety of phases, at wavelengths from the near-ultraviolet through the IR in previous papers (Robinson et al. 2010, 2011), so only a brief description of the model will be presented here.

In our simulations, we divide Earth into a number of equal-area pixels according to the HEALPix scheme (Górski et al. 2005), thus converting the integral in Equation (1) to a sum over the observable pixels. The wavelength-dependent intensity coming from any given pixel is assembled from a lookup table that contains spectra generated over a grid of different solar and observer zenith and azimuth angles. Elements within the lookup table, which are generated using a one-dimensional, line-by-line radiative transfer model (Meadows & Crisp 1996), are computed for a variety of different surface and atmospheric conditions, as well as several different cloud coverage scenarios (e.g., thick, low cloud or thin, high cloud).

To simulate time-dependent changes in Earth’s spectrum we use spatially resolved, date-specific observations of key surface and atmospheric properties from Earth-observing satellites as input to our Earth model. Gas mixing ratio and/or temperature profiles are taken from the Microwave Limb Sounder (Waters et al. 2006), the Tropospheric Emission Spectrometer (Beer et al. 2001), the Atmospheric Infrared Sounder (Aumann et al. 2003), and the CarbonTracker project (Peters et al. 2007). Snow cover and sea ice data as well as cloud cover and optical thickness data are taken from the Moderate Resolution Imaging Spectroradiometer instruments (Salomonson et al. 1989) aboard NASA’s Terra and Aqua satellites (Hall et al. 1995; Riggs et al. 1999). Wavelength-dependent optical properties for liquid water clouds were derived using a Mie theory model (Crisp 1997) and were parameterized using geometric optics for ice clouds (Muinonen et al. 1989).

2.2. Moon Model

Dayside temperatures on the Moon are predominantly determined by the radiative equilibrium established between absorbed solar radiation and emitted thermal radiation (Lawson et al. 2000). Thus, the temperature, \( T \), at any location on the sunlit portion of the Moon is given by

\[ T(\hat{n}, \hat{s}) = \left( \frac{\hat{n} \cdot \hat{s}}{\sigma \epsilon S} \right)^{1/4}, \]  

(2)

where \( A \) is the surface Bond albedo, \( \sigma \) is the Stefan–Boltzmann constant, \( \epsilon \) is the bolometric emissivity of the surface, and \( S \) is the bolometric solar flux density at the Moon’s orbital distance from the Sun (i.e., 1 AU). Since we are focusing on spatially unresolved observations in this study, we assume that \( A \) and \( \epsilon \) do not vary with location on the Moon, using standard globally averaged values of 0.127 and 0.95, respectively (Racca 1995).

Assuming a spatially non-varying Bond albedo and bolometric emissivity allows us to use Equation (1) to write the disk-integrated thermal flux density from the Moon, \( F_{\lambda,M} \), as a function of the star–Moon–observer angle (i.e., the phase angle), \( \alpha \). Thus,

\[ F_{\lambda,M} = \frac{R_M^2}{d^2} \left[ \int_{-\pi/2}^{\pi/2} \int_{-\pi/2}^{\pi/2} \epsilon_\lambda B_\lambda(\theta, \phi) \cos \theta \cos^2 \phi d\phi d\theta \right. \]

\[ + \left. \frac{\pi}{2} \epsilon_\lambda B_\lambda(T_n) (1 - \cos \alpha) \right], \]  

(3)

where \( R_M \) is the radius of the Moon, \( \epsilon_\lambda \) is the wavelength-dependent, global average surface emissivity, \( B_\lambda \) is the Planck function, and \( T_n \) is the lunar nightside temperature. The integral in Equation (3) is over the illuminated portion of the visible disk, and the collection of terms on the second line gives the flux from the lunar nightside. Note that \( \cos \alpha = \hat{n} \cdot \hat{s} \) and, following Sobolev (1975), we can write \( \hat{n} \cdot \hat{s} = \cos(\alpha - \theta) \cos \phi \). We take \( \epsilon_\lambda \) to be an admixture of 17% lunar mare material and 83% lunar highland material, whose emissivity spectra were measured from Apollo lunar samples and taken from the ASTER Spectral Library (http://speclib.jpl.nasa.gov/). Note that we can generalize Equation (3) to Moonlike companions, which we take to be airless bodies similar to the Moon in all ways except size, by varying the value of \( R_M \).
The lunar nightside temperature is measured to be roughly 100 K (Racca 1995), but our model is not sensitive to the specific value that we choose for the nightside temperature since the wavelength-dependent thermal flux coming from such a cold blackbody is more than 100 times smaller than the thermal flux coming from Earth or the full-phase Moon. As noted by Moskovitz et al. (2009), a large day–night temperature contrast for a Moonlike body can be maintained as long as its rotational period is above a certain threshold. For the average lunar surface heat capacity and temperature, this timescale is about 20 hr. Longer rotational periods than this are likely for Moonlike companions to extrasolar Earthlike planets as the timescale for synchronous rotation due to tidal forces (Gladman et al. 1996) is small when compared to the lifetime of a star similar to, or smaller than, the Sun.

Our model does not include a phase-dependent correction to the Moon’s thermal flux that is sometimes incorporated into parameterized spectral models of airless bodies to account for the so-called beaming effect. The effect amounts to corrections at roughly the 10% level or less (Morrison 1973; Mendell & Lebofsky 1982; Lebofsky et al. 1986; Rozitis & Green 2011), which is small enough to be ignored for this study. Note that Equation (3) does not include a reflected solar component. We investigated the importance of reflected sunlight in our results by using the moderate spectral resolution ($\lambda/\Delta\lambda \sim 500$) EPOXI lunar observations (Livengood et al. 2011), which were acquired at a phase angle of 75.1° and spanned 1.0–4.5 $\mu$m. We assumed a Lambert phase function to extrapolate the observations to different phases, and found no significant change in the detectability discussed in later sections. Also, note that, by integrating Equation (3) over wavelength to produce an analytic expression for the phase-dependent bolometric thermal flux, we were able to reproduce the bolometric IR light curves for the Moon from Moskovitz et al. (2009).

3. RESULTS

Temperatures near the sub-solar point on the Moon reach nearly 400 K. As a result, at thermal wavelengths the brightness of some regions on the Moon can be much greater than any region on Earth. In Figure 1, we demonstrate this behavior by comparing a visible light, true color image from NASA’s EPOXI mission, taken at a phase angle of 75.1°, and the same image in 10 $\mu$m brightness temperatures from our Earth and Moon models. Note that intensities from the Moon are quite small in the true color visible image, which is due to the relatively low average visible albedo of the Moon (about 7%, compared to about 30% for Earth). In the thermal image, though, regions near the sub-solar point on the Moon appear brighter than any regions on Earth’s disk. Figure 1 also shows the corresponding disk-integrated flux received at 10 pc for the Moon, Earth, and the combined system. As might be expected, the disk-integrated Earth significantly outshines the disk-integrated Moon, with the Moon typically accounting for less than 10% of the combined flux at most IR wavelengths. However, the Moon contributes as much as 50% of the flux at wavelengths near the 6.3 $\mu$m water band. The following subsections explore the lunar contribution to IR observations of the Earth–Moon system and, furthermore, how the wavelength- and phase-dependent nature of this contribution can be used to detect Moonlike satellites around terrestrial exoplanets.

3.1. Lunar Contribution to Combined Flux

To investigate the extent to which an exoMoon could influence measurements of the disk-integrated spectrum of an exoEarth, we ran our Earth model for a variety of different dates (vernal equinox, as well as mid-northern summer and winter) in 2008 (the most recent year for which CarbonTracker data were available). Seasonal variability in disk-integrated fluxes from Earth were roughly 10%–15% in the 10–12 $\mu$m window region and were generally much smaller at other IR wavelengths, which agrees with the observations published by Hearty et al. (2009).

Figure 2 shows the fluxes received from the Moon, Earth, and the combined Earth–Moon system at two different viewing geometries: full phase and quadrature (50% illumination, phase angle of 90°). In both cases, the observations are averaged over 24 hr at Earth’s vernal equinox, and the observer is viewing
Earth’s orbit edge on and is located over the equator. The spectral resolution in this figure, and all subsequent figures, is taken to be 50, which is consistent with the resolution for planned IR exoplanet characterization missions (Beichman et al. 2006). In the quadrature case, the Moon contributes less than 10% of the net flux from the combined Earth–Moon system at most wavelengths, but contributes nearly 40% of the flux within the 6.3 \( \mu m \) water band and as much as 60% of the flux in the 4.3 \( \mu m \) carbon dioxide band.

The full-phase case presented in Figure 2 shows that it is possible for the Moon to contribute a significant amount of flux to combined Earth–Moon observations. In this scenario, the lunar thermal radiation consistently comprises about 20% of the total signal, approaches 30% of the signal in the 9.6 \( \mu m \) ozone band and the 15 \( \mu m \) carbon dioxide band, makes up as much as 80% of the total signal in the 6.3 \( \mu m \) water band, and exceeds 90% of the signal in the 4.3 \( \mu m \) carbon dioxide band. The added flux within the water band causes the feature to more closely resemble a spectrum of Earth with water vapor mixing ratios artificially lowered to 10% of their present level, creating the appearance of a much drier planet. This effect is demonstrated in Figure 3, where we show the 6.3 \( \mu m \) water band from the full-phase case in Figure 2 along with spectra in which Earth’s water vapor mixing ratios have been artificially scaled to 10% and 1% of their present-day levels.

Figure 4 shows how the additional contribution from the Moon in the full-phase and quadrature cases could confuse brightness temperature measurements and, thus, characterization attempts. At quadrature, brightness temperatures are increased by 5–10 K in the 6.3 \( \mu m \) water band and the 15 \( \mu m \) carbon dioxide band, and by about 15 K in the 4.3 \( \mu m \) carbon dioxide band, as compared to those expected from Earth alone. At full phase, temperatures measured in the 15 \( \mu m \) carbon dioxide band are about 20 K above those expected for Earth alone and, strikingly, temperatures measured in the 4.3 \( \mu m \) carbon dioxide band and the 6.3 \( \mu m \) water band are as much as 30–40 K larger.

In the window region, located between the 4
Figure 5. Simulated observations of both an exoEarth (left column) as well as an exoEarth–Moon system (right column), both at a distance of 10 pc, demonstrating the phase differencing technique which could be used to detect exomoons. Observations are averaged over 24 hr and the spectral resolution is 50. One observation is taken near gibbous phase (solid blue) and another observation is taken near crescent phase, half an orbit later (dashed blue). The gibbous observations occur in the middle of northern summer while the crescent observations occur in the middle of northern winter. The system is assumed to be viewed edge on (inclination of 90°) in the top row (where near gibbous and near crescent observations refer to phase angles of 0° and 180°, respectively), and is viewed at an inclination of 60° in the bottom row (where gibbous and crescent observations refer to phase angles of 30° and 150°, respectively). In the “No Moon” cases, the difference between gibbous and crescent observations (black line) shows only seasonal variability, which is very small in the 4.3 μm carbon dioxide band and the 6.3 μm water band. For the observations in which the Moon is present, these bands are filled in by the lunar flux at gibbous phase, and the difference between the gibbous and crescent observations shows much larger variability within the absorption bands.

3.2. Detecting Exomoons via Phase Differencing

The thermal flux from a slowly rotating, airless companion depends strongly on phase angle (Equation (3)). As a result, an exomoon can present a time-varying signature with a period equal to the host’s orbital period which can be masked by (or mimic) any seasonally dependent thermal flux variations from the host planet. However, the phase-dependent contribution from an exomoon may be detectable by differencing IR observations taken at two different phase angles at wavelengths where the moon is relatively bright and the host planet’s spectrum exhibits only small seasonal variations.

In Figure 5 we demonstrate the differencing approach. An exoEarth (left column, “No Moon”) as well as an exoEarth–Moon system (right column, “Moon”) are observed at a distance of 10 pc at an inclination of 90° (edge on) and 60°. The observations are averaged over 24 hr in either mid-northern summer
or winter. One observation is taken at gibbous phase, at the smallest possible phase angle (which is determined by the inclination), and another observation is taken at crescent phase half an orbit later, at the largest possible phase angle. The difference between these two observations shows only seasonal variability in the Earth-alone case, and shows a combination of the variability from seasons and the Moon in the Earth–Moon case. Without the presence of the Moon, variability within the 4.3 μm carbon dioxide band and the 6.3 μm water band is quite small—on its own, Earth’s spectrum is both dark and stable within these bands. However, when the phase-dependent lunar flux is included, variability in these bands is much larger, and the difference between the near gibbous observation and the near crescent observation closely resembles the gibbous contribution from the Moon, especially since the contribution from the Moon in the near crescent observation is close to zero. Thus, variability within the 4.3 μm carbon dioxide band and the 6.3 μm water is an indicator of the presence of a moon.

We investigate the differencing approach for a wider range of planetary system inclinations and summarize the results in Table 1. Except for inclination, the system parameters are the same as in the previous paragraph. The exoEarth–Moon system is observed near gibbous phase in northern summer and near crescent phase in northern winter, and the observer is placed over the northern hemisphere. Note that system inclination affects the range of possible phase angles that can be observed, and that an inclination of 0° corresponds to viewing the system face on (where the planet and moon would be observed at a constant phase angle of 90°, which is half-illuminated), and an inclination of 90° corresponds to viewing the system edge on (where the planet and moon go through the entire range of phase angles over the course of an orbit). Bands spanning 4.2–4.5 μm and 5.0–7.5 μm (in the 4.3 μm carbon dioxide band and 6.3 μm water band, respectively) were found to be ideal for detecting the lunar signal, where a balance must be achieved between a wide enough band for photon collection and a narrow enough band to exclude seasonal variability outside the absorption feature. In addition, Table 1 shows flux ratios for the exoEarth–Moon system, which demonstrates the significance of the exoMoon’s brightness in the aforementioned bands, as well as inferred brightness temperatures for the Earth twin (assuming that the observer is ignorant of the contamination by, and presence of, the companion).

Table 1 also shows an estimate of the minimum required signal-to-noise ratio (S/N) for the gibbous and crescent phase observations of the exoEarth–Moon system such that the difference of the observed system fluxes at these two phases within specified wavelength ranges would measure the gibbous phase lunar flux at an S/N of 10. By simple error propagation on the difference between the gibbous and crescent phase flux measurements, this S/N is given by $S/N = \sqrt{F_G^2 + F_C^2}/(F_G - F_C)$, where S/N is the S/N for the robust measurement of the gibbous phase lunar flux (which we take to be 10, although the results scale linearly with whichever S/N one takes to represent a robust measurement), and $F_G$ and $F_C$ are the gibbous and crescent phase fluxes, respectively, for the planet–moon system through a given bandpass. Table 1 shows estimates of the S/N required for detection in the 4.3 μm carbon dioxide band and the 6.3 μm water band for a Moon twin and for a body twice the size of the Moon.

In the 4.2–4.5 μm range, the gibbous phase flux from the exoMoon is more than 300% larger than the exoEarth’s flux variability for a wide range of phases. As a result, the S/N required to detect the exoMoon’s thermal signal is rather small (between 10–20) for all inclinations above 30°. At inclinations below about 30°, where the system is being observed closer to face on, therefore limiting all observations to phases near half illumination, the crescent phase lunar flux is a sizeable fraction of the gibbous phase flux, causing the crescent phase flux to contaminate the measurement of the gibbous phase lunar flux when subtracting the observations taken at different phases.

In the 5.0–7.5 μm range, the exoEarth’s variability begins to wash out the gibbous phase thermal flux from the exoMoon at inclinations below about 45°. At inclinations above this, the required S/N for detection is only slightly larger than 20, and is close to 10 for companions twice the size of the Moon. In general, contamination from the exoEarth’s seasonal variability and the crescent phase lunar signal cause the differencing technique to work poorly for inclinations below about 30°–45°. For inclinations above this, detecting Moonlike satellites via the differencing technique may be feasible, depending on the capabilities of the telescope.

4. DISCUSSION

Surface, tropospheric, and stratospheric temperatures on Earth are typically within the range of 200–300 K, and extreme day/night temperature differences do not occur due to atmospheric circulation and relatively large surface and atmospheric heat capacities. The Moon, in contrast, has a relatively low surface heat capacity and lacks an atmosphere with which to redistribute energy from the dayside to the nightside of the world. As a result, surface temperatures on the Moon are as high as 400 K at the sub-solar point, allowing the Moon to contribute a significant amount of flux to IR observations of the Earth–Moon system (depending on phase). Furthermore, the large lunar dayside temperatures cause the peak of the lunar thermal spectrum to be located at wavelengths distinct from the peak of Earth’s thermal spectrum. Near full phase, the peak of the lunar thermal spectrum occurs near the 6.3 μm water band, causing the Moon to outshine Earth both at these wavelengths as well as in the 4.3 μm carbon dioxide band.

In the following paragraphs we discuss our results in the context of characterizing terrestrial exoplanets. We begin by discussing the contributions of the Moon to spatially unresolved observations of Earth. Next we discuss how a phase-dependent signal from a satellite can confuse interpretations of seasonality. This is followed by a discussion of how we might detect an exomoon via phase differencing. Finally, we present some ideas for future investigations.

Effects of a satellite on the characterization of an exoEarth. When observing an unresolved Earth–Moon system, thermal flux from the Moon disproportionately affects regions of Earth’s spectrum where Earth has strong absorption bands. As a result, characterization of Earth’s atmospheric composition and temperature from IR observations taken by a distant observer could be strongly influenced by the Moon. For example, for full-phase observations of the Earth–Moon system, lunar thermal radiation consistently comprises about 20% of the total signal, makes up as much as 80% of the total signal in the 6.3 μm water band (creating the appearance of a much drier planet), and over 90% of the signal in the 4.3 μm carbon dioxide band. Current models predict that large impacts like the Moon-forming impact should be common and that conditions present in the debris disk following such an impact cause any
Table 1
Phase Differencing Technique for Detecting Exomoons: Thermal Fluxes, Flux Ratios, Brightness Temperatures, and Estimated S/N Requirements

| Inc (°) | Flux (10^{-20} W m^{-2}) | F_M/F_E | T_b (K) | Flux (10^{-23} W m^{-2}) | F_M/F_E | T_b (K) | Flux (10^{-21} W m^{-2}) | F_M/F_E | T_b (K) | R_M | 2R_M |
|--------|----------------------------|---------|--------|----------------------------|---------|--------|----------------------------|---------|--------|-----|------|
| 90     | 10.6 (9.6)                 | 2.6 (<0.1) | 24 (<1) | 272 (251)                  | 3.0 (2.4) | 14.1 (<0.1) | 480 (<1)                  | 272 (234) | 3.6 (3.2) | 3.8 (<0.1) | 110 (<1) | 266 (241) | 12 (22) | 11 (13) |
| 75     | 10.6 (9.3)                 | 2.5 (<0.1) | 23 (<1) | 271 (249)                  | 3.0 (2.2) | 13.7 (<0.1) | 450 (<1)                  | 271 (232) | 3.6 (3.0) | 3.7 (<0.1) | 100 (<1) | 266 (240) | 12 (21) | 11 (13) |
| 60     | 10.5 (8.9)                 | 2.3 (0.1)  | 21 (1)  | 270 (247)                  | 3.2 (2.0) | 12.3 (<0.1) | 390 (2)                   | 270 (231) | 3.6 (2.9) | 3.3 (<0.1) | 90 (1)   | 264 (239) | 13 (23) | 11 (13) |
| 45     | 10.5 (8.6)                 | 1.9 (0.1)  | 18 (2)  | 267 (245)                  | 3.2 (1.8) | 10.2 (0.2)  | 320 (10)                  | 266 (231) | 3.5 (2.7) | 2.8 (0.1)  | 80 (4)   | 261 (238) | 14 (25) | 11 (14) |
| 30     | 10.5 (8.4)                 | 1.6 (0.5)  | 15 (4)  | 265 (245)                  | 3.3 (1.7) | 7.8 (0.7)   | 240 (40)                  | 262 (234) | 3.5 (2.6) | 2.2 (0.3)  | 60 (1)   | 258 (239) | 16 (33) | 12 (17) |
| 15     | 10.5 (8.4)                 | 1.2 (0.5)  | 11 (6)  | 263 (246)                  | 3.3 (1.7) | 5.4 (1.7)   | 170 (100)                 | 257 (240) | 3.5 (2.6) | 1.6 (0.6)  | 50 (2)   | 255 (241) | 25 (60) | 18 (28) |
| 0      | 10.5 (8.5)                 | 0.8 (0.8)  | 8 (8)   | 261 (249)                  | 3.2 (1.8) | 3.3 (3.3)   | 100 (180)                 | 252 (247) | 3.5 (2.7) | 1.0 (1.0)  | 30 (4)   | 251 (245) | 30 (4)  | 30 (4)  |

Notes.

a Brightness temperatures are computed using the net flux from the system assuming a size of one Earth radius in the conversion from flux to intensity.
b A “detection” constitutes measuring the excess gibbous phase lunar flux at an S/N of 10, which is accomplished by differencing the gibbous and crescent phase observations of the system. Estimates of the required S/N are shown for a body with a radius equal to the Moon’s radius (R_M), and for a body twice as large as the Moon. S/N calculations are further described in the text.
companions formed from debris material to be depleted in volatiles. Thus, contamination of IR observations of extrasolar terrestrial planets due to unresolved, airless companions may be a common reality, and these results will generally apply to thermal IR observations taken by future exoplanet detection and characterization missions.

It is important to point out that contamination from airless companions can be minimized by taking observations as near as is feasibly possible to new phase, where the illuminated fraction of the planet and companion is small, minimizing flux from the warmer dayside. However, depending on the orbital inclination of the system, observations at small illuminated fractions (i.e., large phase angles) may not be accessible. For example, a planet–moon system viewed in a face-on orbit will always be at an illuminated fraction of 50% (a phase angle of 90°). In this case, the contribution from the companion will be nearly constant and relatively small, except in some absorption bands (Figure 2, second panel).

Phase-dependent variability and seasonality. The contribution from an airless companion depends strongly on phase angle and, thus, can mimic seasonally dependent thermal variations from the host planet. Figure 5 demonstrates how significant this effect can be for Earth and the Moon. A simulated exoEarth–Moon system is observed at gibbous phase in the middle of northern summer so that the lunar signal adds to the seasonal variability in the exoEarth’s spectrum, causing the flux variations in the atmospheric window region to appear roughly twice as large as the Earth-only case. If the presence of the companion goes undetected, then it appears as though the exoEarth has very exaggerated seasons. If the gibbous observation were to occur instead in the middle of northern winter, then the lunar contribution would wash out the seasonal variations from the exoEarth, and the variability in the atmospheric window region would decrease to nearly zero. This would create the false appearance of a planet with almost no seasonal climate variability and an inferred low obliquity. These findings further demonstrate how the presence of an undetected companion can interfere with the measurement of the obliquity and thermal properties of the host planet, and are in good agreement with the bolometric results in Moskovitz et al. (2009).

Detecting exomoons using phase-dependent variability. The ability of a companion to an extrasolar terrestrial planet to outshine its host within molecular absorption bands proves to be useful as the phase-dependent variability in the companion’s brightness can impart a detectable signal in spatially unresolved observations of the planet–companion system. The broadband models of Moskovitz et al. (2009) did not capture this important behavior, causing them to conclude that only large satellites (roughly Mars-sized) of Earth-like exoplanets could be detected by NASA’s Terrestrial Planet Finder (TPF). As shown in Table 1, it may be feasible to detect smaller exomoons by differencing gibbous phase and crescent phase observations of the planet–moon system at wavelengths where the gibbous moon is bright and the planet’s spectrum is relatively dark and stable.

In the case of Earth and the Moon, the peak in the gibbous phase Moon’s spectrum is at about 7 μm, which is near the 4.3 μm carbon dioxide band and the 6.3 μm water band, where the escaping flux from Earth is relatively small and stable over seasonal timescales. As a result, bands spanning these features are well suited to detecting an exoMoon, whose variability could be detected with observations taken at an S/N of about 10–20. Searching for excesses due to an exomoon in the 4.3 μm carbon dioxide band is attractive since CO$_2$ is a common well-mixed gas in terrestrial planetary atmospheres. Using the 6.3 μm water band will be useful for habitable exoplanets which, almost by definition, will present a deep water band and whose moons will be receiving a stellar flux similar to what the Moon receives, heating these companions to temperatures similar to our Moon. It is important to note that acquiring observations at S/Ns of 10–20 in the depths of these bands may be quite difficult. While some planned IR exoplanet characterization missions may acquire observations at an S/N of 10 (Beichman et al. 1999; Cockell et al. 2009), a large integration time would be required to make such an observation in the 4.3 μm carbon dioxide band and, to a lesser extent, the 6.3 μm water band as there is relatively little flux coming from an exoEarth–Moon system at these wavelengths, especially near crescent phase where the exoMoon is not particularly bright. Furthermore, current science requirements for planned IR exoplanet characterization missions typically adopt a shortwave cutoff around 6.5 μm, which does not reach the bottom of the 6.3 μm water band or the 4.3 μm carbon dioxide band (Beichman et al. 2006; Cockell et al. 2009).

If integration time or shortwave cutoff considerations make exomoon detections in the aforementioned bands infeasible, it may be possible to use the 15 μm carbon dioxide band, which is not as close to the peak of the gibbous phase Moon’s spectrum as or seasonally stable as the previously discussed bands. Detecting the base of the 15 μm carbon dioxide band is much more feasible than detecting the base of the 4.3 μm carbon dioxide band. It may be possible, using a combination of modeling and observations, to detect an exomoon by comparing measurements and variability within these two bands, even if the crescent phase base of the 4.3 μm band is not detected.

Future work. Interesting investigations for the future include pairing our models with reverse/retrieval models for terrestrial exoplanets to further explore the extent to which an exomoon could confound spectroscopic characterization of an exoEarth. Our Earth model is dependent on input data from Earth-observing satellites, so that we cannot apply the current model to terrestrial planets with seasonal cycles different from those on Earth. However, pairing our spectral model of Earth to a three-dimensional general circulation model for Earthlike planets is a task that would enable us to model time-dependent, high-resolution spectra of terrestrial planets with distinct climates from Earth. Such a study would allow us to understand whether or not the 6.3 μm water band is stable enough to allow for the detection of exomoons around planets with high obliquity angles or planets with eccentric orbits (i.e., planets with more extreme seasons than Earth). This pairing would also allow us to study whether or not the 7.7 μm methane band is well suited to detecting thermal excesses from moons orbiting planets analogous to the early Earth, which was expected to have much higher atmospheric methane concentrations than the modern Earth (Kasting et al. 2001).

5. CONCLUSIONS

Depending on viewing geometry, the Moon can contribute a significant amount of flux to IR observations of the spatially unresolved Earth–Moon system, especially at wavelengths where there are strong absorption bands in Earth’s spectrum. For an extrasolar Earth–Moon system observed at full phase, the Moon consistently comprises about 20% of the total signal at most wavelengths, and makes up as much as 80%–90% of the total.
signal in the 6.3 $\mu$m water band and the 4.3 $\mu$m carbon dioxide band. The added flux in the water band creates the appearance of a more desiccated planet, resembling the spectrum of Earth with atmospheric water vapor mixing ratios artificially lowered to 10% of their present values. Furthermore, the added lunar flux can increase inferred brightness temperatures for Earth by as much as 40 K at some wavelengths. Thermal flux from an airless exomoon depends strongly on phase angle, so that by differencing observations taken near crescent phase from those taken near gibbous phase, at wavelengths where the host planet’s spectrum is relatively stable over seasonal timescales, it may be possible to detect the excess thermal radiation coming from a Moon-sized companion in the gibbous phase observations using a $\text{TPF}$-like telescope.

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