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The global energy balance of Titan

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[1] The global energy budget of planets and their moons is a critical factor to influence the climate change on these objects. Here we report the first measurement of the global emitted power of Titan. Long-term (2004–2010) observations conducted by the Composite Infrared Spectrometer (CIRS) onboard Cassini reveal that the total emitted power by Titan is $(2.84 \pm 0.01) \times 10^{14}$ watts. Together with previous measurements of the global absorbed solar power of Titan, the CIRS measurements indicate that the global energy budget of Titan is in equilibrium within measurement error. The uncertainty in the absorbed solar energy places an upper limit on the energy imbalance of 6.0%. **Citation:** Li, L., et al. (2011), The global energy balance of Titan, *Geophys. Res. Lett.*, *38*, L23201, doi:10.1029/2011GL050053.

1. Introduction

[2] The energy budget is a critical factor in determining the weather and climate on planets and satellites. Significant energy imbalance has been detected for the giant planets [*Ingersoll et al.*, 1975; *Orton and Ingersoll*, 1980; *Hanel et al.*, 1981, 1983; *Pearl et al.*, 1990]. The emitted thermal energy exceeds the absorbed solar energy by 57%, 80%, and 157% for Jupiter, Saturn, and Neptune, respectively [*Conrath et al.*, 1989; *Ingersoll*, 1990]. Such an energy imbalance is thought to be linked to the internal heat, which provides important clues to the understanding of planetary evolution and atmospheric circulation on the giant planets. On the other hand, Earth's global energy budget is in a near equilibrium state [*Trenberth et al.*, 2009]. A recent study [*Hansen et al.*, 2005] suggests that the global energy budget has a small imbalance with the absorbed solar energy exceeding the emitted thermal energy by just 0.4%. Even though the energy imbalance is very small, it has significant influences on global warming and climate changes on Earth [*Hansen et al.*, 2005]. Titan, the biggest satellite of Saturn, is similar to Earth in many ways. Here, we explore a fundamental question: Is the global energy budget on Titan in an equilibrium state?

[3] To evaluate the global energy budget of Titan, both the absorbed solar energy and the emitted thermal energy must be measured. The absorbed solar energy is determined by the bolometric Bond albedo with the known total solar radiance. The Bond albedo of Titan has already been measured based on observations by (1) Earth-based telescopes [*Younkin*, 1974], (2) the imaging photopolarimeter onboard the Pioneer spacecraft [*Tomasko and Smith*, 1982], and (3) a combination of spacecraft and Earth-based telescopes [*Neff et al.*, 1985]. Even though these measurements were conducted at different times, the Bond albedo of Titan is approximately consistent between all three measurements.

[4] Unfortunately, there are no direct measurements of the global emitted thermal radiance before the epoch of Cassini, mainly because of a lack of infrared observations with sufficient spectral range and spatial coverage. An energy balance between the absorbed solar energy and the emitted thermal energy was simply assumed in previous measurements of Titan's Bond albedo [*Younkin*, 1974; *Tomasko and Smith*, 1982; *Neff et al.*, 1985]. On the other hand, some investigators [*Low and Rieke*, 1974; *Caldwell*, 1977] noted that the global energy budget of Titan could be imbalanced, and the energy imbalance could reach as much as 38% with an inversion model of Titan's atmosphere. The inconsistency of such studies makes it important to measure the global emitted radiance of Titan. Such measurements provide not only important constraints on the energy budget of Titan but also critical clues regarding to the climate change on the moon.

2. Data and Methodology

[5] The direct computation of emitted power P_{emit} requires measurements of the spectral flux over a wide range of wavenumbers and emission angles [*Chandrasekhar*, 1950; *Goody and Yung*, 1989; *Hanel et al.*, 2003]. The Composite Infrared Spectrometer (CIRS) of Cassini [*Flasar et al.*, 2004] provides such measurements, which have not been conducted before. Figure 1 displays an example of a CIRS averaged spectrum of Titan. These are recorded by three focal planes (FP1, FP3, and FP4) with total wavenumber coverage of 10–1430 cm^{-1} ($\sim$7–1000 μm). The wavenumber coverage is much better in the CIRS on Cassini than in the infrared instruments on Pioneer/Voyagers [*Li et al.*, 2010]. Figure 1 shows that the radiance observed by FP1, which mainly comes from the atmospheric layers around the tropopause [*Flasar et al.*, 2004], is dominant in the total emitted power of Titan. Figure 1 also demonstrates

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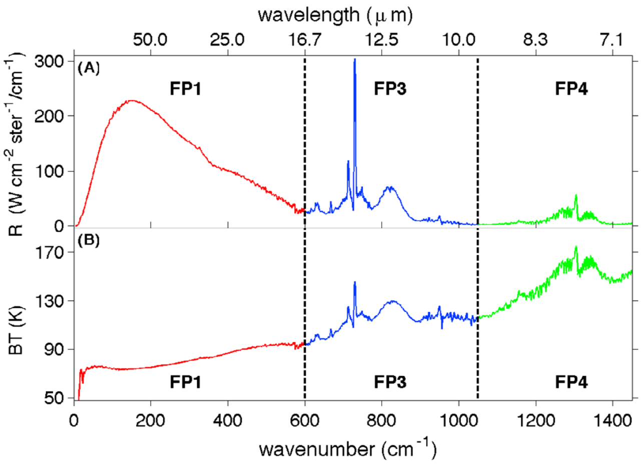

Figure 1. Combined spectral radiance from the three spectral ranges covered by FP1, FP3, and FP4. The combined spectrum has wavenumber covering 10–600 cm^{-1}, 600–1050 cm^{-1}, and 1055–1430 cm^{-1}, for FP1, FP3, and FP4, respectively. The example shown in Figure 1, which was recorded at a spectral resolution of 2.5 cm^{-1}, is an average of spectra over the whole year of 2007 with a latitude range of 30°N-30°S and emission angle range of 0 ~ 30°. (a) CIRS radiance. (b) Corresponding brightness temperature.

some emission/absorption bands in the stratosphere recorded by FP3 and FP4, which have relatively warmer brightness temperatures.

[6] In order to precisely measure the total emitted power of Titan, we select a reference altitude, in which there is no downward thermal flux. In other words, the reference level is selected to be an altitude above which there are no any gases or particles emitting thermal flux. At some latitudes of the northern hemisphere, there is significant thermal emission up to nearly 500 km [*Achterberg et al.*, 2008]. Therefore, we set the reference altitude as 500 km in this study. In the CIRS data, the emission angle and latitude are referenced to the solid surface of Titan. The reference altitude of 500 km is a significant fraction of the solid body radius R_T ~ 2575 km [*Zebker et al.*, 2009], so the variation of emission angle and latitude along a radiance ray cannot be ignored. We calculate a new emission angle and latitude at the reference altitude along the radiance ray path from the original CIRS emission angle and latitude as described in the auxiliary material.[1]

3. Results

[7] All Titan spectra with two spectral resolutions (15.5 cm^{-1} and 2.5 cm^{-1}), which were recorded during the time period of 2004–2010, were used to compute the emitted power of Titan. The processing of the CIRS raw spectra is similar to the method used in our previous study of Saturn's emitted power [*Li et al.*, 2010]. The final data are two-dimensional (latitude × emission angle) matrices of wavenumber-integrated radiances of Titan with 1° resolution in both latitude and emission angle at the reference altitude of 500 km. Figure 2a is the final processed matrix, which displays Titan's spectrally-integrated radiance between 2004 and 2010. The nearly complete coverage of emission angle shown in Figure 2, which does not exist in the previous observations, makes the Cassini/CIRS observations a perfect data set to explore Titan's emitted power.

[8] There are still a few observational gaps at high emission angles and in the polar region (Figure 2a). In order to enable numerical integration over the whole plane of emission angle and latitude, we use a least-square fit to interpolate/extrapolate from existing observations to fill observational gaps in Figure 2, as described in our previous study of Saturn [*Li et al.*, 2010]. After filling observational gaps, we then integrate the radiance over the direction of emission angle to get the emitted power at each latitude. The resulted emitted power is displayed in Figure 2b. The uncertainty shown in Figure 2b is estimated by a combination of errors from (1) this procedure for filling observational gaps and (2) the calibration of CIRS spectra for removing the radiance of the background from the radiance of the target [*Flasar et al.*, 2004], which is discussed in our previous study [*Li et al.*, 2010]. The meridional distribution of the emitted power shows a basic symmetry between the two hemispheres even though they are in different seasons

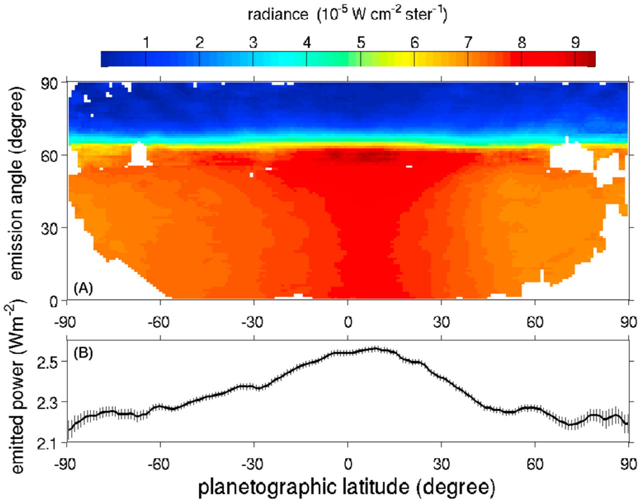

Figure 2. Coverage of CIRS observations and the emitted power of Titan at the reference altitude of 500 km. (a) Time mean (2004–2010) wavenumber-integrated radiance in the plane of latitude and emission angle. The wavenumber-integrated radiance in Figure 2a is over the spectral range of 10–1430 cm^{-1}. The radiance with emission angle less than 57° at the altitude of 500 km comes from CIRS nadir observations, and the radiance with emission angle larger than 57° comes from CIRS limb observations. All CIRS observations of Saturn's atmosphere with two spectral resolutions (15.5 cm^{-1} 2.8 cm^{-1}) between October 2004 and November 2010 are averaged. CIRS observations with other spectral resolutions, which have negligible spatial coverage, are not included in this study. (b) Meridional distribution of the emitted power. The thick line is the profile of the emitted power and vertical lines represent the uncertainties. The estimated uncertainty is combined by the uncertainty related to the filling observational gaps and the uncertainty related to the calibration.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL050053.

during the observational period of 2004–2010 (solar longitude from 293° to 6°; northern mid-winter to northern spring equinox). The radiative time constant of Titan's troposphere is probably longer than 100 Earth years [*Flasar et al.*, 1981], which explains why the seasonal signal does not show up in the meridional distribution of the emitted power.

[9] The meridional distribution of the emitted power shown in Figure 2 is further utilized to calculate the global average emitted power $\overline{P}_{emit}$ [*Ingersoll et al.*, 1975; *Li et al.*, 2010]. The global average of emitted power and effective temperature (i.e., the temperature of a blackbody emitting the same emitted power) at the reference altitude (500 km) are 2.392 ± 0.010 watts/meter^2 and 80.59 ± 0.08 K, respectively. The reference altitude of emitted power (i.e., 500 km) is higher than the altitude corresponding to the radius of Titan's limb in the visible spectrum of solar radiance. The limb radius of Sun's peak radiation was estimated as 2825 km [*Smith*, 1980; *Tomasko and Smith*, 1982], which corresponds to an altitude ~250 km relative to the solid body radius (2575 km). Rescaling the results from the reference altitude (500 km) to the altitude of Sun's peak radiation (250 km) by keeping the total emitted power from different spheres (i.e., the sphere with radius of $R_T + 500$ and the sphere with radius of $R_T + 250$) constant, we have the global average of emitted power and effective temperature at the altitude of 250 km are 2.834 ± 0.012 watts/meter^2 and 84.08 ± 0.09 K, respectively. The new direct measurements of effective temperature (i.e., 84.08 ± 0.09 K) are basically consistent with the previous indirect estimate (i.e., 84 ± 2 K) referred at the altitude of 250 km [*Tomasko and Smith*, 1982], but the new measurements are one-order of magnitude more precise than the previous indirect estimates.

[10] The consistence of effective temperature between the Cassini measurements and the previous indirect measurements suggests the global energy balance on Titan. Here, we further examine the global energy budget and its uncertainty by comparing the total emitted power and the total absorbed power on Titan. Based on the emitted power at the reference altitude (500 km), we have the total emitted power of Titan as $P_{emit} = 4\pi\,(R_T + 500)^2\overline{P}_{emit}$, where the solid body radius R_T has a values of 2575 km [*Zebker et al.*, 2009]. Therefore, Titan's total emitted thermal power is (2.84 ± 0.01) × 10^{14} watts. The solar irradiance at 1 AU is 1366 watts/meter^2 [*Willson and Mordvinov*, 2003], so we have the average solar irradiance is 15.7 watts/meter^2 during the time period of Cassini (i.e., 2004–2010). The variation of total solar irradiance at Titan is less than 0.1% between different solar cycles [*Willson and Mordvinov*, 2003; *Lean and Rind*, 2009], which is neglected in our discussion of energy balance on Titan. The measurements of reflected solar radiance suggest the average Bond albedo is 0.265 ± 0.03 [*Younkin*, 1974; *Tomasko and Smith*, 1982; *Neff et al.*, 1985]. The radius of the limb of Titan for the wavelength of Sun's peak radiation (i.e., 0.48 μm) was estimated as 2825 km [*Smith*, 1980; *Tomasko and Smith*, 1982], which is basically consistent with recent studies based on radiation models [*McKay et al.*, 1989; *Toon et al.*, 1992; *Tomasko et al.*, 2008]. The solar radiation at different wavelengths penetrates to different altitudes, so the radius of the limb varies with wavelengths. The previous estimate [*Toon et al.*, 1992] suggested that the radius of limb varies ~100 km around the radius at the peak radiation (i.e., 2825 km) across the whole solar spectrum, which suggests that there is about 3.5% variation in the limb radius. The 3.5% variation in the limb radius is significantly smaller than the uncertainty in the Bond albedo (i.e., 0.03/0.265 ~ 11.3%). Therefore, only the uncertainty of Bond albedo is considered in the following estimates of the uncertainty of absorbed solar power. The total absorbed solar power can be expressed as $P_{absorb} = \pi R_L^2 I_S(1 - A)$, where R_L is the radius of limb of Titan at 0.48 μm, I_S is the solar constant at Titan, and A is the Bond albedo. Based on the known values of these parameters, we have the total absorbed solar power of Titan as (2.89 ± 0.12) × 10^{14} watts.

[11] Comparing the total absorbed solar power of (2.89 ± 0.12) × 10^{14} watts with the total emitted thermal power of (2.84 ± 0.01) × 10^{14} watts, we find that the global energy budget of Titan is in equilibrium within the measurement error of absorbed solar energy. The CIRS measurements of emitted energy are one-order of magnitude more precise than the previous measurements of the absorbed solar energy, so the primary uncertainty in determining the energy balance comes from the uncertainties of the absorbed solar radiance. We use the uncertainties of absorbed solar radiance to estimate the upper limit of the possible energy imbalance. The range of absorbed solar energy is from 2.77 × 10^{14} watts to 3.01 × 10^{14} watts, which suggests that the difference between the absorbed solar energy and the emitted thermal energy varies from −2.5% ((2.77–2.84)/2.84 ~ −2.5%) to 6.0% ((3.01–2.84)/2.84 ~ 6.0%). Therefore, the possible energy imbalance cannot exceed 6.0%, which excludes the possibility of large energy imbalance on Titan.

4. Conclusions

[12] Our analyses suggest a basic equilibrium of global energy budget on Titan, but we cannot rule out the possibility of a small energy imbalance on the satellite due to the uncertainty of the Bond albedo in the previous measurements. It is possible to obtain more precise measurements of the Bond albedo based on the observations from the Cassini ISS and VIMS instruments. Wavelengths of ISS (0.26–1.0 μm) and VIMS (0.35–5.1 μm) occupy nearly the complete spectral range of solar radiance. With a good coverage of phase angle by the extensive observations of Cassini during the period of 2004–2010, the reflected radiance recorded by the two instruments (ISS and VIMS) can be utilized to measure the Bond albedo of Titan at a much better precision than before. In addition, the long-term global observations conducted by Cassini make it possible to study the variation of energy balance in space and time (e.g., season) on the satellite. Precise measurements of energy balance and its distribution in space and time will provide one more perspective to investigate the climate changes on Titan in addition to the greenhouse [*McKay et al.*, 1991] and anti-greenhouse [*McKay et al.*, 1999] effects.

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