Titan's Global Radiant Energy Budget During the Cassini Epoch (2004-2017)

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Key Points:

- With Cassini multiinstrument observations (CIRS, ISS, and VMIS), we provide measurements of the seasonal variations of Titan's Bond albedo
- Our measurements suggest a net energy excess (2.9 ± 0.8% of the emitted energy) over the Cassini era (2004–2017) on Titan
- The energy imbalance changes from an energy excess (10.7 ± 0.7%) in 2004–2005 to an energy deficit (−3.4 ± 0.6%) in 2017

Supporting Information:

Supporting Information may be found in the online version of this article.

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Titan's Global Radiant Energy Budget During the Cassini Epoch (2004–2017)

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Abstract Radiant energies of planets and moons are of wide interest in the fields of geoscience and planetary science. Based on long-term multiinstrument observations from the Cassini spacecraft, we provide here the first observational study of Titan's global radiant energy budget and its seasonal variations. Our results show that Titan's radiant energy budget is not balanced over the Cassini era (2004–2017) with the absorbed solar energy $(1.208 \pm 0.008) \times 10^{23}$ J larger than the emitted thermal energy $(1.174 \pm 0.005) \times 10^{23}$ J. The energy imbalance is 2.9 ± 0.8% of the emitted thermal energy. Titan's global radiant energy budget is not balanced either at the timescales of Earth's years and Titan's seasons. In particular, the energy imbalance can be beyond 10% of the emitted thermal energy at the timescale of an Earth year. The energy imbalance revealed in this study has important impacts on Titan, which should be examined further by theories and models.

Plain Language Summary The radiant energy budget is a fundamental metric for planets and moons. Using the observations from the Cassini spacecraft, we first look at Titan's global radiant energy budget and its seasonal variations. Our study suggests Titan's global radiant energy budget is not balanced at the timescales of Earth years and Titan's seasons. The energy imbalance can help us better understand the characteristics of Titan (e.g., seasonal variations). Titan's energy imbalance also suggests that it is possible that there are more terrestrial planets and moons having unbalanced radiation budgets. Finally, Titan's time-varying radiant energies imply that the internal heat of the giant planets needs to be reexamined by considering the temporal variations of radiant energies.

1. Introduction

The radiant energy budget of a planet or a moon, which is determined by the absorbed solar energy and the emitted thermal energy (Conrath et al., 1989), plays a critical role in determining thermal characteristics of the astronomical body. Such a radiant energy budget can help us understand the geology of terrestrial planets (e.g., polar ices of Mars) (McCleese et al., 2007), internal heat related to the formation and evolution of giant planets (e.g., Hubbard, 1980; Smoluchowski, 1967), and subsurface intrinsic heat driving the jet plumes on some moons (e.g., Howett et al., 2011; Spencer & Nimmo, 2013). For terrestrial bodies with atmospheres, the radiant energy budget at the top of atmosphere also sets critical boundary conditions for the atmospheric systems (Peixoto & Oort, 1992). The transfer and distribution of radiant energies (i.e., the absorbed solar energy and the emitted thermal energy) within the atmospheric systems modify the thermal structure to generate available potential energy. The available potential energy can be converted into kinetic energy to drive atmospheric circulation and the related weather and climate (e.g., Lorenz, 1955; Read et al., 2016; Schubert & Mitchell, 2013).

Currently, Earth and Titan are the only two astronomical bodies with significant atmospheres and surface seas in our solar system. For our home planet, some recent studies (Hansen et al., 2005; Trenberth et al., 2016) revealed a small energy imbalance: the absorbed solar energy exceeds the emitted thermal energy by a magnitude of 0.2%–0.4% of the emitted energy. These studies further suggest that the small energy imbalance is related to global warming and climate change on Earth. Compared with numerous studies of the radiant energy budget on our home planet, observational studies of Titan's global radiation budget are relatively lacking. Titan is similar to Earth in many ways (e.g., surface pressure, liquid lakes/oceans on the surface, and greenhouse atmosphere). On the other hand, the orbit around the Sun is much more elliptical for Titan (eccentricity ~ 0.057) than for Earth

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(eccentricity ~ 0.017). Titan's large eccentricity means that the solar flux at Titan varies beyond 20% on its orbital path. Therefore, Titan probably has a much more dynamical radiant energy budget than that of Earth. Here, we want to examine the temporal variations of Titan's radiant energy budget to see if there is any energy imbalance.

The Cassini spacecraft (Jaffe & Herrell, 1997) was an international orbiter that explored the Saturn system including Titan from 2004 to 2017. The Cassini multiinstrument observations have made it possible to precisely examine the global radiant energy budget of Titan for the first time. In this study, we use observations from the Imaging Science Subsystem (ISS) (Porco et al., 2004) and the Visual and Infrared Mapping Spectrometer (VIMS) (Brown et al., 2004) to examine Titan's Bond albedo, which is defined as defined as the ratio between the reflected (or scattered) solar radiation and the incident solar radiation. At each wavelength, we further define such a ratio as monochromatic Bond albedo (Li et al., 2018). The Cassini ISS observations were used to examine different behaviors of Titan's reflected solar irradiance between low and high phase angles (Garcia Munoz et al., 2017), but Titan's Bond albedo and its temporal variations in the Cassini epoch have not been examined yet. The Cassini ISS and VIMS observations have many advantages over previous observations (e.g., better spatial resolution, better coverage of phase angle, and better coverage of wavelength) (Creecy et al., 2019; Li et al., 2010, 2011, 2018), so we expect to get the best measurements of Titan's Bond albedo and hence the absorbed solar power. Combined with our measurements of Titan's emitted thermal power (Creecy et al., 2019), we can determine Titan's global radiant energy budget. Furthermore, long-term Cassini observations (2004–2017) provide a great opportunity to take a first look at the seasonal variations of Titan's radiant energy budget.

The methodology of computing Titan's Bond albedo and hence the absorbed solar power is briefly introduced in Section 2. The Cassini observations and the other data sets used in this study are introduced and summarized in Table S1 and Figures S1–S7 in Supporting Information S1. Titan's troposphere and stratosphere, which play dominant roles in absorbing the solar irradiance, extend to a few hundred kilometers. Therefore, Titan's optical radius in which the solar irradiance is effectively absorbed and reflected (i.e., effective radius) is substantially larger than its solid radius (~2,575 km) (Zebker et al., 2009). The effective radius, which varies with wavelength, is discussed in detail in the Supporting Information (Figures S8–S15 in Supporting Information S1). We basically follow a method from a previous study (Smith, 1980), in which the maximal radiance contrast is used to determine the edge of the effective radius. We first validate the method using Cassini observations of Enceladus (Figure S8). Then we apply the method to measure Titan's effective radius as a function of wavelength (Figures S9–S12 in Supporting Information S1), which are consistent with previous observational and theoretical studies (Figures S13–S15 in Supporting Information S1).

We then calculate Titan's full-disk albedo by integrating the ISS and VIMS calibrated radiance over the disks with the effective radii, which is also discussed in Supporting Information (Figures S16–S31 in Supporting Information S1). The comparison of Titan's full-disk albedo between the ISS and VIMS analyses (Figure S16 in Supporting Information S1) suggests that the two instruments provide consistent results. We also conduct the comparisons of Titan's full-disk albedo between the Cassini analyses and previous analyses based on other observations (Figures S17–S19 in Supporting Information S1), which also validate the Cassini analyses. After validating the computation of full-disk albedo, we organize the Cassini data in the two-dimensional domain of time and phase angle (Figure S20 in Supporting Information S1). There are observational gaps in phase angle and wavelength in the Cassini ISS and VIMS observations, and we use least squares fitting (Bevington & Robinson, 2003; Li et al., 2018) to fill in the observational gaps (Figures S21–S29 in Supporting Information S1). Then, we obtain Titan's full-disk albedo in the two-dimensional domain with complete coverage of phase angle and wavelength for each year from 2004–2005 to 2017 (Figure S30 in Supporting Information S1). Finally, we have the monochromatic geometric albedo, the monochromatic phase integral, and the monochromatic Bond albedo at each wavelength for the Cassini epoch (Figure S31 in Supporting Information S1). Based on the distribution of the monochromatic Bond albedo (Figure S31 in Supporting Information S1), we can compute Titan's Bond albedo by weighting the monochromatic Bond albedo with the solar spectral irradiance.

The uncertainties in the measurements of Titan's Bond albedo and hence the absorbed solar power mainly come from the calibration errors of the Cassini ISS and VIMS data, the uncertainties related to filling the observational gaps, and the uncertainties in determining Titan's effective radii at different wavelengths. We discuss these uncertainties in Supporting Information (Figures S32–S47 in Supporting Information S1). We also discuss the uncertainties of Titan's emitted power (the other component of Titan's radiant energy budget), even though such uncertainties were already investigated in our previous studies of Titan's emitted power (Creecy et al., 2019; Li

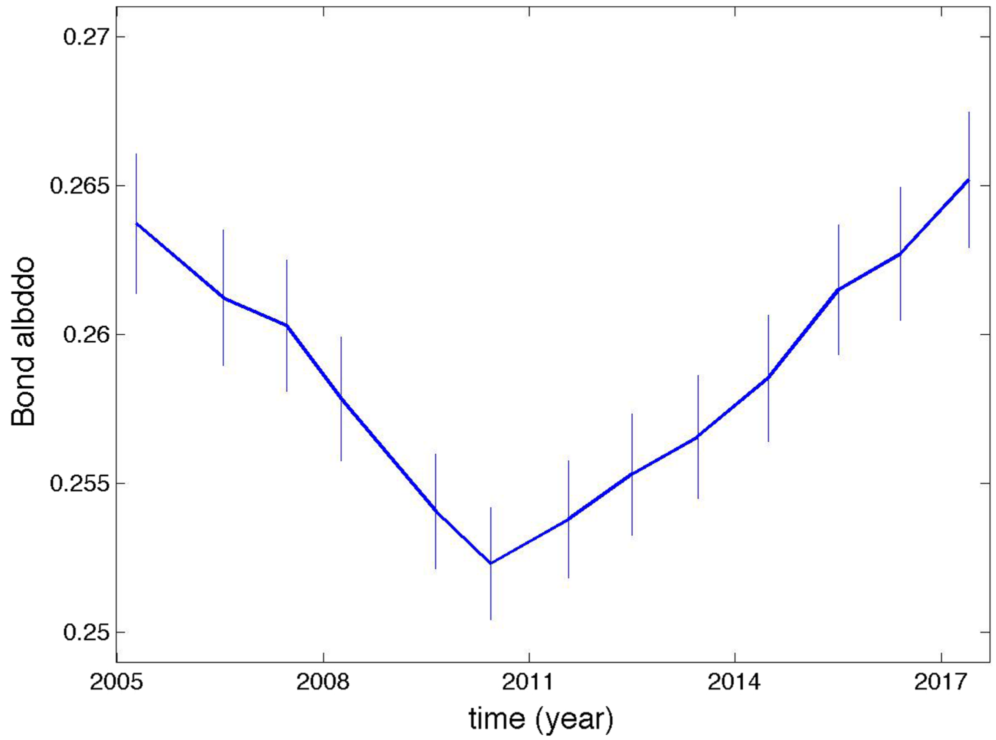

Figure 1. Titan's Bond albedo from 2004–2005 to 2017. Vertical lines represent measurement uncertainties. There are only 3 months (October-December) of high-quality observations in 2004, so the 2004 observations are combined with the 2005 observations.

et al., 2011). It should be mentioned that we have consider all possible uncertainty sources to the best of our ability but it is still possible that there are more uncertainty sources.

2. Results

Figure 1 shows Titan's Bond albedo during the Cassini epoch. Titan's Bond albedo continuously decreased from 0.264 ± 0.003 in 2004–2005 to 0.252 ± 0.002 in 2010 by a percentage change of $4.6 \pm 1.4\%$. After that, it increased from 0.252 ± 0.002 in 2010 to 0.265 ± 0.003 in 2017 by $5.2 \pm 1.4\%$. The nonmonotonic variation of Bond albedo is probably related to the 15-year oscillations of Titan's full-disk albedo examined in limited wavelengths (e.g., Neff et al., 1985; Younkin, 1974). Furthermore, the nonmonotonic variation makes Titan's Bond albedo slightly increase by $0.4 \pm 1.6\%$ during the Cassini epoch.

Titan's Bond albedo was measured in previous studies (Neff et al., 1985; Younkin, 1974), but these studies were based on observations with very limited coverage of wavelength and phase angle. The Cassini observations are much better than these previous observations, so the analysis based on the Cassini observations provides improved measurements of Titan's Bond albedo. The temporal variations of Titan's monochromic Bond albedos at some wavelengths were explored in previous studies (Lockwood & Thompson, 2009; Sromovsky et al., 1981), but the investigations of the temporal variations of Titan's Bond albedo had not been done before. The Cassini long-term observations provide the first examination of the seasonal variations of Titan's Bond albedo and hence the radiant energy budget.

Combining Titan's measured Bond albedo and the known solar power at Titan, we can compute the total reflected solar power and the total absorbed solar power, which are shown in Figure 2. The total solar power at Titan continuously decreased ~18.6% from 4.307×10^{14} W in 2004–2005 to 3.508×10^{14} W in 2017, which is much stronger than the temporal variations of Bond albedo shown in Figure 1. The temporal variations of the total reflected solar power (panel B) and the total absorbed solar power (panel C) basically follow similar variations of the total solar power (panel A). The total reflected solar power continuously decreased by

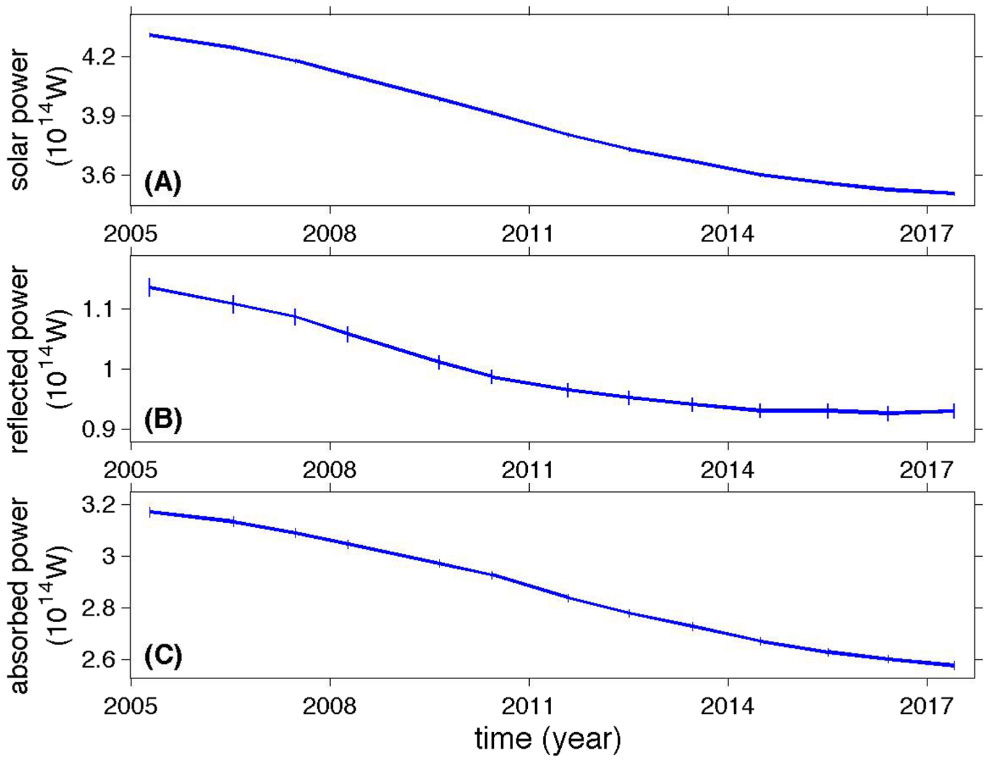

Figure 2. Titan's total solar power, reflected power, and absorbed solar power from 2004–2005 to 2017. (a) Total solar power over Titan. (b) Total solar power reflected by Titan. (c) Total solar power absorbed by Titan. Vertical lines in the three panels represent measurement uncertainties.

18.1 ± 1.4% from (1.136 ± 0.013) × 10^{14} W in 2004–2005 to (0.930 ± 0.010) × 10^{14} W in 2017. Correspondingly, the total absorbed solar power decreased by 18.7% ± 0.5% from (3.170 ± 0.013) × 10^{14} W in 2004–2005 to (2.577 ± 0.010) × 10^{14} W in 2017.

Figure 3 shows the comparison between the absorbed power from this study and the emitted power measured in our previous study (Creecy et al., 2019). The decrease in the absorbed power (18.7% ± 0.5%) is much stronger than the decrease of emitted power (6.8 ± 0.4%) for the Cassini epoch. The ratio between the net radiant energy (i.e., the absorbed power—the emitted power) and the emitted power changed from 10.7 ± 0.7% in 2004–2005 to −3.4 ± 0.6% in 2017. Therefore, Titan's radiant energy budget is significantly dynamic. There is an energy excess (i.e., the absorbed solar energy > the emitted thermal energy) at some seasons and an energy deficit (i.e., the absorbed solar power < the emitted thermal power) at other seasons. At the timescale of an Earth year, the radiant energy imbalance can be more than 10% sometimes (e.g., 2005). Titan's significant energy deficit and excess at the relatively short timescales (e.g., an Earth year and a Titan season) are caused by its large orbit eccentricity (~0.057), and hence largely varying distance between Titan and the Sun. With the varying distance, the solar flux changes quickly (solar flux is proportional to $1/r^2$, where r is the distance between Titan and the Sun). The combination of the dramatic change of solar flux and the relatively weak variation of Bond albedo means that the absorbed solar power varies strongly (Figure 2). On the other hand, the temporal variation of the emitted power is relatively weak because of the large thermal inertial and long radiative time constant of the atmospheric layers mainly contributing to Titan's emitted power (Creecy et al., 2019; Li et al., 2011). The change of emitted power cannot match the change in the absorbed solar power at the timescales of Earth years and Titan's seasons. Therefore, the energy deficit and excess occur in these timescales.

We also integrate the absorbed solar power and the emitted thermal power over the time period of 2004–2017 to get the total absorbed solar energy and the total emitted thermal energy during the Cassini epoch. The total absorbed solar energy (1.208 ± 0.008) × 10^{23} J is larger than the total emitted thermal energy (1.174 ± 0.005) × 10^{23} J, which suggests that they are not balanced even for the Cassini epoch. The difference between the two energies ((0.034 ± 0.009) × 10^{23} J) is 2.9 ± 0.8% of the total emitted thermal energy.

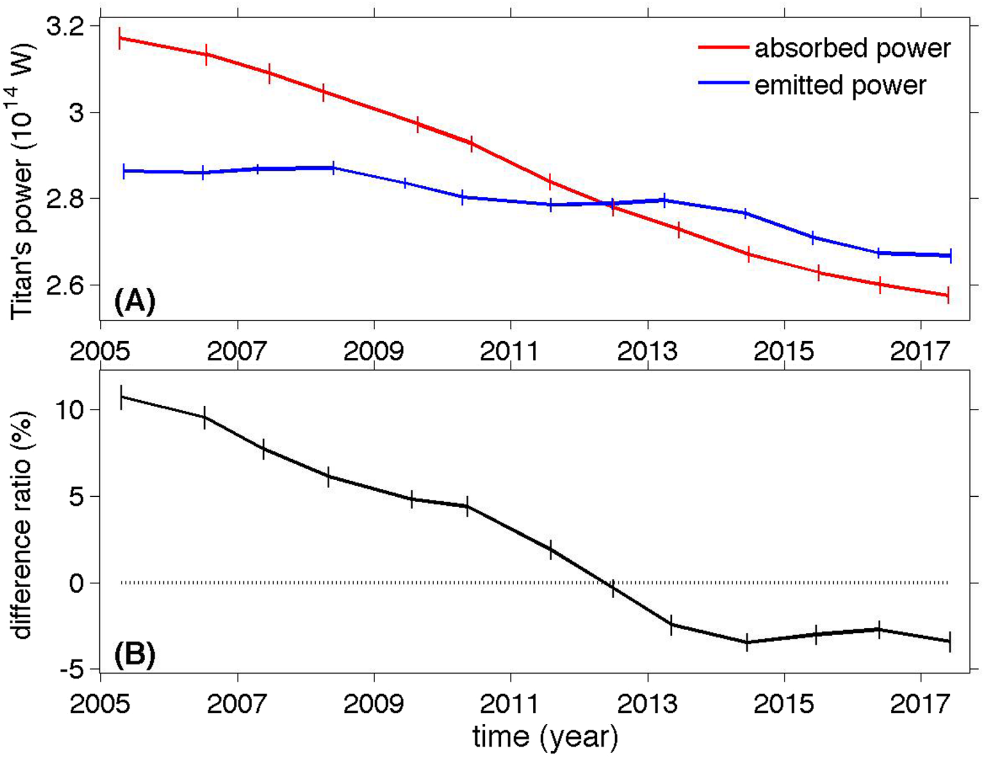

Figure 3. Comparison between Titan's absorbed solar power and emitted thermal power during the Cassini epoch. (a) Comparison between the absorbed solar power (red line) and the emitted thermal power (blue line). The measurements of Titan's emitted power are from our previous study (Creecy et al., 2019). (b) The ratio between the net radiant energy (i.e., absorbed power-emitted power). and the emitted power. The horizontal dashed line is the reference line with the ratios equating zero. The vertical lines in the two panels represent measurement uncertainties.

The Cassini observational time (~14 years) is about one half of Titan's year (~29.424 years). To gain further insight of the annual radiant energy budget of Titan, we extrapolate the Cassini results to a complete Titan year by fitting the observed absorbed and emitted powers with an assumption that the seasonal cycles of the absorbed and emitted powers follow sine functions (Figure S48 in Supporting Information S1). Such fitting suggests an even larger energy imbalance (5.0% ± 2.1% of the total emitted thermal energy) between the total absorbed solar energy and the total emitted thermal energy over a complete Titan year. However, the extrapolated result should be used with caution. First, it is likely that Titan's radiant energies (especially the emitted thermal energy) do not follow simple sinusoidal functions. Second, the Cassini observations show that Titan's emitted power has significant fluctuation with time (Figure 3) and we cannot rule out that such fluctuation is even stronger at the times outside the Cassini epoch.

3. Discussion

Whether or not Titan's radiant energy budget is balanced in a Titan year or longer times, the Cassini observations suggest that Titan's radiant energy budget is not balanced at the timescales of Earth years and Titan's seasons. In particular, the energy imbalance can be beyond 10% at the timescale of Earth years (Figure 3). Such a large energy imbalance will significantly affect Titan's atmospheric circulation and weather. To better characterize the effects of the energy imbalance on Titan's atmosphere and surface, we need further information (e.g., the vertical and meridional distributions of the energy imbalance inside atmosphere and possible energy imbalance at the surface). Considering that the stratospheric hazes play important roles in Titan's radiant energy budget (e.g., Read et al., 2016) and the stratosphere has a relatively short radiative time constant (Bezard et al., 2018; Flasar et al., 1981), the energy imbalance would trigger some quick responses (e.g., warming) of Titan's stratosphere if the revealed energy imbalance mainly happens in the stratosphere. The radiative time constants can be longer than a Titan year for Titan's lower troposphere (Bezard et al., 2018), so the response will take longer time if the energy imbalance mainly happens in the troposphere. It is also possible that the energy imbalance can reach the surface and affect its thermal characteristics.

The responses of Titan's atmosphere and surface to the energy imbalance can help warm up Titan's atmosphere (or surface) and hence increase Titan's emitted power, which can potentially serve as a restoring force to help equilibrate the radiant energy budget after the Cassini epoch. It is hard to estimate Titan's response time due to lacking information on the vertical distribution of energy imbalance. In addition, we do not know if the responses are strong enough to compensate the energy imbalance during the Cassini epoch to equilibrate Titan's radiant energy budget. We cannot rule out the possibility that Titan's energy imbalance exists at timescales of a Titan year and even longer. If Titan has an energy imbalance at long timescales, such an energy imbalance can contribute to climate change, similar to what happens on Earth. On Earth, oceans are the main reservoir for the radiant energy imbalance (Hansen et al., 2005; Levitus et al., 2000). On Titan, the hazes in the atmosphere are significant absorbers of solar irradiance (Read et al., 2016). These hazes along with Titan's surface that has lakes/oceans both can possibly serve as the reservoir for the radiant energy imbalance.

If the energy imbalance at the timescales of a Titan year and longer really exists on Titan, a question should be asked: what is the cause of such an imbalance? Compared to the seasonal variations of solar flux at Titan (Figure 2), the temporal variations of Titan's Bond albedo are small (Figure 1), so the absorbed solar power basically follows the seasonal variations of solar flux (Figure 2). The comparison of Titan's full-disk Bond albedo between the Cassini observations and the observations before the Cassini epoch (Neff et al., 1985; Younkin, 1974) suggests that Titan's Bond albedo is relatively stable with time even though cloud bands can modify Titan's regional albedo (see Figure S43 in Supporting Information S1), so we expect that the temporal variations of Titan's absorbed solar power will basically follow the seasonal cycle of solar flux even at timescales longer than one Titan year. In other words, Titan's absorbed solar power has stable periodic variations. So, the energy imbalance revealed in the Cassini epoch and the possible long-term energy imbalance most likely come from the behaviors of emitted power. The hazes and greenhouse gases play important roles in modifying the thermal structure of Titan's atmosphere and surface by anti-greenhouse and greenhouse effects (McKay et al., 1991), respectively. The hazes and the greenhouse gases vary at Titan's seasons (Aharonson et al., 2009; West et al., 2018) and longer timescales (Lorenz et al., 1997), in which the temporal variations of haze distribution and methane abundance are driven by not only the eccentricity of Titan's orbit around the Sun but also the long-term interaction between Titan's atmosphere and surface. Some of the strong temporal variations can potentially modify Titan's thermal structure and hence the emitted power to a certain extent and disequilibrate Titan's radiant energy budget. It should be mentioned that it is still possible there are other unidentified factors, which can trigger and/or maintain the possible long-term energy imbalance on Titan.

The energy imbalance revealed in this study can help us better understand the roles of Titan's radiant energy budget in the system of Titan. Due to lacking observation, an assumption of a balanced radiant energy budget is used in the current theories and models (e.g., Goody, 2007; Read et al., 2016; Schubert & Mitchell, 2013). It will be useful for theories and models of Titan's atmosphere and climate (e.g., Lebonnois et al., 2012; Lora et al., 2015; Newman et al., 2011) to examine the impacts of the revealed energy imbalance at the timescales of Earth years and Titan's seasons on Titan's seasonal variations and the related processes. The analysis of Titan's radiant energy budget also suggests that it is possible that there are more terrestrial planets and moons having unbalanced radiant energy budgets at different timescales. There are relatively few observations and studies for the radiant energy budgets of the planets and moons other than Earth and Titan. The global radiant energy budgets of Mars and Venus are assumed to be balanced in current theories and models (e.g., Goody, 2007; Read et al., 2016; Schubert & Mitchell, 2013), but the Titan results show it is important to examine this assumption. Considering the importance of the radiant energy budget and the critical roles of the possible energy imbalance in climate change, we propose more missions and observations to measure the radiant energy budgets of terrestrial planets and moons.

Finally, the temporal variations of Titan's radiant energy budget illustrate that the radiant energy budget is a dynamic process. Most of the previous measurements of the radiant energy budgets of planets and moons are based on snapshot observations, and the temporal variations of the radiant energies were not adequately addressed. Our analyses suggest that the temporal variations of radiated energies must be considered when examining the radiant energy budget especially for the planets and moons with relatively large eccentricities. The radiant energy budget has also been used to estimate the internal heat on the giant planets (Conrath et al., 1989), but the temporal variations of radiant energies have not been fully considered yet for the estimates of the internal heat. That means the internal heat of the giant planets needs to be critically examined by considering the temporal variations of the radiant energies.

Data Availability Statement

The Cassini raw data used in this study are publicly available from NASA Planetary Data System (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/Cassini/Cassini.html). In particular, the Cassini Imaging Science Subsystem (ISS) and Visual and Infrared Mapping Spectrometer (VIMS) data sets, which are analyzed in this study, can be downloaded from https://pds-imaging.jpl.nasa.gov/volumes/iss.html, and https://pds-imaging.jpl.nasa.gov/volumes/vims.html, respectively. The information of the ISS and VIMS onboard the Cassini spacecraft and the data products of the two instruments are described in detail in two papers by Porco et al. (2004) (https://doi.org/10.1007/s11214-004-1456-7) and Brown et al., 2004 (https://doi.org/10.1007/s11214-004-1453-x), respectively.

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