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Key Points:
- The giant storm significantly modified Saturn's global radiant energies
- Our results suggest that Saturn's internal heat should be reexamined
- We also suggest a mechanism to trigger giant storms on Saturn

Supporting Information:
- Text S1 and Figures S1–S5

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Saturn's giant storm and global radiant energy

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Abstract We analyze the relationship between Saturn's radiant energies and the 2010 giant storm with the Cassini observations. The storm increased the emitted power in a wide latitudinal band (20–55°N) with a maximum change of $9.2 \pm 0.1\%$ around 45°N from 2010 to 2011. Such a regional change caused the global-average emitted power to increase by $\sim 2.0 \pm 0.2\%$. Saturn's giant storm occurs quasiperiodically (i.e., period approximately one Saturnian year), so it is possible that giant storms continuously modify the emitted power if the storm modification has a lifetime close to one Saturnian year. The hemispheric-average emitted power in the southern hemisphere, which was mainly affected by the seasonal change, decreased by $8.5 \pm 0.3\%$ from 2004 to 2013. Our estimates also imply that the 2010 giant storm significantly modified the absorbed solar power of Saturn. The significant temporal variations of radiant powers should be considered in reexamining the value of Saturn's internal heat flux.

1. Introduction

Giant storms with bright clouds covering more than a hundred thousand kilometers in the longitudinal direction and a couple of tens of thousand kilometers in the latitudinal direction are one of the amazing events that occur on Saturn. Such a giant storm erupted in early December 2010 on Saturn [*Sanchez-Lavega et al.,* 2011; *Fischer et al.,* 2011; *Fletcher et al.,* 2011]. With unprecedented observations by ground-based telescopes and the Cassini spacecraft, many important characteristics of dynamical and thermal structures of this giant storm have been revealed. The visible part of the giant storm disappeared in the middle of 2011 [*Sanchez-Lavega et al.,* 2012; *Sayanagi et al.,* 2013], but the thermal structure modified by the giant storm lasted at least till 2014 [*Fletcher et al.,* 2012; *Achterberg et al.,* 2014]. In this study, we investigate the relationship between the giant storm and the radiant energies as revealed in long-term observations from the Cassini spacecraft. We mainly use the infrared spectra recorded by the Cassini Composite Infrared Spectrometer (CIRS) [*Flasar et al.,* 2004] to measure the emitted power of Saturn emphasizing its relationship to the 2010 giant storm. We follow the methodology developed in our previous study [*Li et al.,* 2010] to compute the global emitted power of Saturn. In addition, images taken by the Cassini Imaging Science Subsystem (ISS) [*Porco et al.,* 2004] are used to estimate the clouds and the reflected solar radiance modified by the giant storm.

2. Observations and Analyzed Results

The observational times of the Cassini/CIRS measurements during the period of 2004–2013 are outlined in Table 1. The coverage of the CIRS observations in the plane of latitude and emission angle is shown in Figure S1 in the supporting information. Figure S1 shows some observational gaps, especially in 2010 and 2011. For these latitudes where there are enough observational data, we use the linear interpolation/extrapolation technique [*Li et al.,* 2010, 2011, 2012] to fill the observational gaps in the direction of emission angle. For these latitudes where there are insufficient observational data to perform linear interpolation/extrapolation (e.g., the polar regions in 2010 and 2011), we use linear interpolation in time to fill the observational gaps. After filling the observational gaps, we integrate the thermal radiance in the direction of emission angle to obtain the emitted power at each latitude, which is displayed in Figure 1.

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Table 1. Average Observational Times and the Corresponding Solar Longitudes and Subsolar Latitudes[a]

Average Observational Time	Solar Longitude	Subsolar Latitude
July 2005	306.9°	20.7°S
June 2007	333.5°	11.6°S
June 2008	345.9°	6.3°S
May 2009	357.5°	1.1°S
May 2010	9.9°	4.4°N
June 2011	22.1°	9.7°N
July 2012	35.6°	15.2°N
April 2013	43.8°	18.1°N

[a]Solar longitude is defined as the angular distance along Saturn's orbit around the Sun measured from northern spring equinox (0°). The solar longitude is used to differentiate different seasons on Saturn (i.e., northern spring 0–90°, northern summer 90–180°, northern autumn 180–270°, and northern winter 270–360°). Subsolar latitude is the latitude on a planet where the solar insolation is normal to the surface, 1 bar level on gas planets. The spatial coverage of observations in each year of 2004–2006 is too incomplete to compute the global emitted power, so observations in the 3 years (2004–2006) are combined together.

Figure 1 shows that there are clear temporal variations of global emitted power during the period of 2004–2013. At most latitudes, the temporal variations are significantly larger than the measurement uncertainties, which are estimated by considering the observational gaps and data calibration [*Li et al.,* 2010]. From 2010 to 2011, Saturn's emitted power strongly increased between 20°N and 55°N, a latitudinal band in which the thermal structure was modified by the giant storm [*Fletcher et al.,* 2012; *Achterberg et al.,* 2014]. The increase in the wide latitude band also created an additional local maximum of emitted power around 35°N that has existed since 2011. The maximum increase in the latitude band of giant storm (20°N–55°N), which is around 45°N, reaches 9.2 ± 0.1% from 4.35 ± 0.04 W/m in 2010 to 4.75 ± 0.04 W/m in 2011. Such strong variation includes the seasonal variation. The measurements in the latitudes of the Northern Hemisphere (NH) (e.g., 19°N and 56°N), which are close to the latitude band of the giant storm (20°N–55°N), suggest that the temporal variation of emitted power due to the seasonal variation is ~1.6–3.2%. The seasonal variation (~1.6–3.2%) is much smaller than the total variation in the storm latitudes (e.g., ~ 9.2 ± 0.1% at 45°N), which suggests that the giant storm played dominant roles in the temporal variation of emitted power in the storm latitudes. In the latitudes outside the range of the giant storm in the NH, Saturn's emitted power displays relatively small temporal variations compared to the strong variations in the storm latitudes. The relatively weak temporal variations are related to the seasonal change in the NH.

In the Southern Hemisphere (SH), the continuous decrease of emitted power is also related to the seasonal change of Saturn, in which the subsolar latitude changed from the SH to the NH during the period of 2004–2013 (Table 1). In addition, the decrease of solar constant due to the increase of Sun-Saturn distance during the period of 2004–2013 (Figure S2) contributes to the decrease of emitted power in the SH. Finally, Saturn's rings, which block part of the solar radiance to the SH when the subsolar latitude moved to the NH (Figure S3), contribute further to the decrease of emitted power in the SH. Figure 2a suggests that the combination of effects caused the hemispheric-average emitted power in the SH to decrease by 8.5 ± 0.3% from 5.41 ± 0.01 W/m in 2004–2006 to 4.95 ± 0.01 W/m in 2013. On the other hand, the NH-average emitted power increased by 5.7 ± 0.3% from 4.60 ± 0.01 W/m in 2004–2006 to 4.86 ± 0.01 W/m in 2013, mainly due to the 2010 giant storm. The increase in the NH and the decrease in the SH help to weaken the large hemispheric asymmetry in the meridional profile in 2004–2009 [*Li et al.,* 2010]. Figure S4 is the comparison between the Cassini profiles (Figure 1) and the Voyager profile, which suggests that the Cassini profiles are approaching the Voyager profile with time

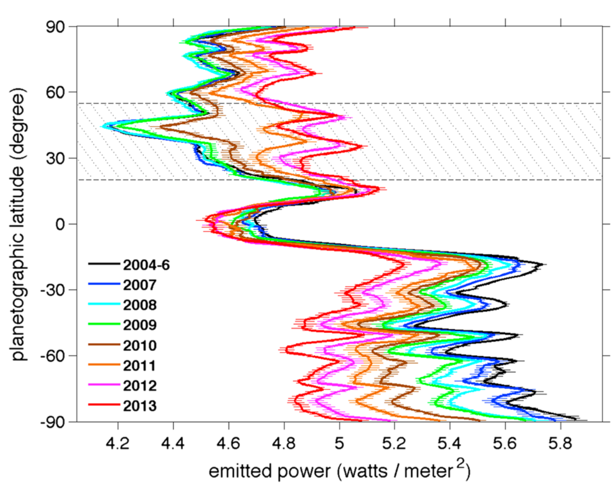

Figure 1. Meridional distribution of Saturn's emitted power during the period of 2004–2013. The thick line is the profile of the emitted power, and horizontal error bars represent the uncertainties. The shading area between 20°N and 55°N represents the latitudinal band with the modified thermal structure due to the 2010 giant storm.

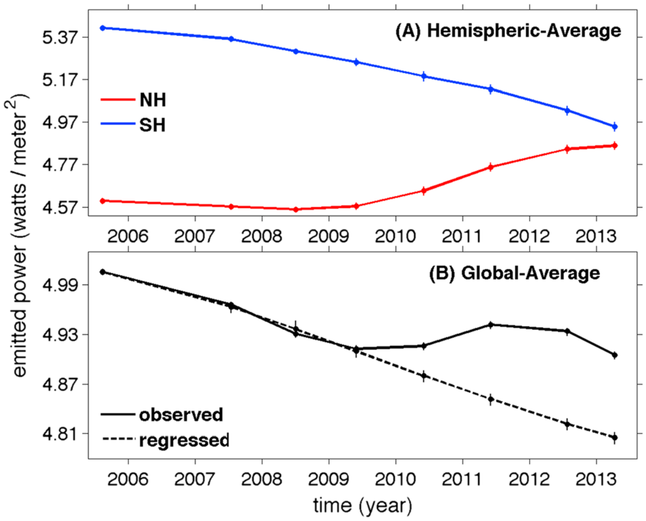

Figure 2. Spatial-average emitted power during the period of 2004–2013. (a) The hemispheric-average emitted power. (b) The comparison of global-average emitted power between observation and regression. The observed emitted power is based on Figure 1, and the regressed emitted power is based on the solar constant at Saturn in Figure S2.

especially in the SH. The seasonal variation contributes to the difference in the SH between the Cassini epoch and the Voyager epoch. However, there is still difference in the SH between the Voyager epoch (1980–1981) profile and the Cassini 2011 profile, which are separated by one Saturnian year. Therefore, Saturn's emitted power also displays interannual variability in which the mechanism is unknown. In the NH, large difference of emitted power exists between the Voyager profile and all Cassini profiles. It seems that the seasonal variation and giant storms (e.g., the 2010 one) both play roles in the SH variability of emitted power from the Voyager epoch to the Cassini epoch. On the other hand, we are not sure if the spatial distribution of emitted power affects the eruption and development of giant storms on Saturn. The 2010 giant storm erupted around the minimum of zonal winds [*García-Melendo et al.,* 2011] and also close to the global minimum of emitted power in 2010 (Figure S5). The possible mechanisms of the minima contributing to the eruption of the giant storm should be further explored.

We also calculate the global-average emitted power (Figure 2b) based on the Cassini profiles (Figure 1). The correlation between the solar constant (Figure S2) and the emitted power during the period of 2004–2009 is 0.995 with confidence level larger than 99%, which suggests that the temporal variation of global-average emitted power is mainly determined by the seasonal cycle of the solar constant before the eruption of the 2010 giant storm. The solar constant continuously decreased from 2009 to 2013 (Figure S2), which suggests that the increase of global-average emitted power around 2010–2011 is related to the giant storm. The natural seasonal variation and the giant storm both affected the global-average emitted power since 2010. Based on the high correlation between the solar constant (Figure S2) and the emitted power during the time period without the giant storm (2004–2009), we can extrapolate the emitted power from 2004–2009 to 2010–2013 by linear regression [*Bevington and Robinson,* 1992] and assuming there are no giant storms in the time period of 2010–2013. The regressed emitted power (Figure 2b) represents the temporal variation solely affected by the seasonal change of solar constant. Therefore, we can differentiate the effects of the seasonal cycle of solar constant from the giant storm by this way. The difference between the regressed emitted power and the observed emitted power can be used to estimate the effects of the giant storm on the global-average emitted power, which suggests that the giant storm modified the global-average emitted power by ~0.10 ± 0.01 W/m (~2.0 ± 0.2%). Figures 1 and 2 suggest that modifications to the emitted power due to the giant storm still existed in 2013, so the lifetime of the modification of emitted power is longer than three Earth years. We do not know how long this effect will last. It is possible that modifications to the emitted power have a lifetime comparable to the radiative time constant of the atmospheric layers involved in the emitted power (~24 Earth years) [*Conrath et al.,* 1989], which is close to the Saturnian year (~29.4 Earth years). Considering that giant storms have occurred with a quasiperiodical mode about one Saturnian year [*Sanchez-Lavega et al.,* 2012], it is likely that giant storms continuously modify Saturn's emitted power.

In addition to the emitted power, the 2010 giant storm also affected the Bond albedo and hence the absorbed solar energy (the other energy component of radiant energy budget) by generating very bright clouds. The solar constant at the top of the atmosphere (Figure S3) sets a baseline for the absorbed solar energy. Once the reflected solar radiance is determined, we can estimate the absorbed solar energy from the total solar radiance (Figure S3). Precise measurements of the reflected solar radiance, which require the complete coverage of phase angle and carefully accounting for the rings effects, are complicated. Here we

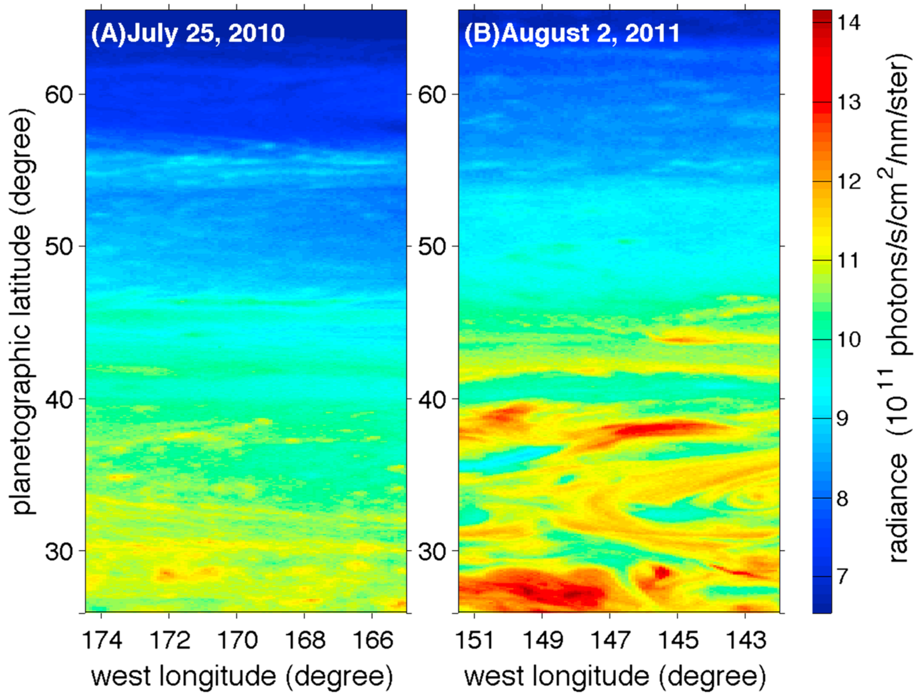

Figure 3. Comparison of reflected solar radiance between prestorm and poststorm. The two raw Cassini/ISS images recorded at wavelength of 750 nm have the same phase angle ~ 15°, which are calibrated by the ISS calibration software—CISSCAL (Cassini ISS CALibration) [*West et al.,* 2010].

conduct a preliminary estimate of the effects of the 2010 giant storm on the reflected solar radiance. Figure 3 shows a comparison of two Cassini ISS images between July 2010 (before the storm) and August 2011 (after the storm) at the wavelength of 750 nm observed at the same phase angle (15°). The two images are calibrated by the Cassini ISS calibration software [*West et al.,* 2010]. The comparison shown in Figure 3 suggests that the reflected solar radiance at the wavelength of 750 nm changed by ~ 7% from 2010 to 2011 in the latitudinal band of bright clouds generated by the giant storm (25–45°N). The area of the latitude band of bright clouds (25–45°N) is ~14% of Saturn's global area, so we have the bright clouds generated by the storm increased the global-average reflected solar radiance by ~ 1% at the wavelength of 750 nm. The variations of reflected solar radiance related to the giant storm are different at different wavelengths [*Sanz-Requena et al.,* 2012]. The storm-related variations of reflected solar radiance also display different behaviors in different time periods. The Cassini observations suggest that the bright clouds generated by the 2010 storm, which increased the reflected solar radiance, lasted for approximately one Earth year [*Sanz-Requena et al.,* 2012*; Sayanagi et al.,* 2013]. Then the bright clouds disappeared by late 2011, leaving a remarkably clear atmosphere resulting in probably a decrease in the reflected solar radiance that exists at least to 2014 [*Momary and Baines,* 2014]. Therefore, the giant storms affect the reflected solar radiance and hence the absorbed energy in a very complicated way, which is being investigated in an independent study.

3. Conclusions and Discussions

In summary, the Cassini observations suggest that the 2010 giant storm significantly affected Saturn's radiant energy budget and its temporal variation. The temporal variations of energy components (i.e., emitted thermal energy and absorbed solar energy) affect our estimates of the internal heat of Saturn. In general, the excess of the emitted thermal power over the absorbed solar power is used to estimate the value of the internal heat on the giant planets [e.g., *Smoluchowski,* 1967*; Salpeter,* 1973*; Flasar,* 1973*; Stevenson and Salpeter,* 1976]. Most of the previous estimates of internal heat are based on the snapshot observations (please refer to the review paper by *Conrath et al*. [1989]). The temporal variations of energy components were not considered in the estimates of internal heat in the previous studies. Our investigations suggest that the 2010 giant storm can strongly modify the regional emitted thermal power and absorbed solar power in a wide latitudinal band. The seasonal change contributes further to the temporal variation of Saturn's radiance energies. At the hemispheric scale, the SH-average emitted power decreased by ~8.5% from 2004 to 2013, which is mainly due to the seasonal change. After 2013, the subsolar latitude moves northward until 2017 (summer solstice of the NH). In addition, the Sun-Saturn distance monotonically increases, and hence, the solar constant at Saturn continuously decreases ~4.2% from 2013 to 2017. Therefore, we expect that the SH-average emitted power will decrease further at least until 2017. The extended Cassini observations will help us examine the temporal variations of emitted power until some time in 2017, depending on when the last regional radiometric observations are obtained. The SH-average emitted power probably keeps decreasing a few years after 2017 considering the long radiative time constant of the atmospheric layers involved in the emitted power (~24 Earth years). At the global scale, the seasonal changes [*Li et al.,* 2010] and the 2010 giant storm (this study) both modify Saturn's emitted power with a magnitude of a few percentages. Such variation is much smaller than the temporal variation of solar constant (e.g., ~19.1% from 2004 to 2017) and the related absorbed solar power. The temporal variation of emitted power measured in this study and the previous study [*Li et al.,* 2010] will be combined with the proposed complicated computations of Saturn's absorbed solar energy to refine Saturn's internal heat in one independent study.

The 2010 giant storm played important roles in Saturn's radiant energy budget. On the other hand, it will be interesting to explore the roles of the radiant energy budget in generating the giant storms on Saturn. The computation of solar radiance at the top of atmosphere including rings effects (Figure S3) suggests that the solar radiance increased significantly over the latitudes occupied by the 2010 giant storm after Saturn's northern spring equinox in August 2009. However, the emitted power in the storm latitudes did not change significantly until the eruption of the giant storm in December 2010 (Figure 1). The excess of solar energy possibly triggers the giant storm during springtime in the NH. The solar heating cannot penetrate to the atmospheric levels deeper than 1–2 bars [*Perez-Hoyos and Sanchez-Lavega,* 2006]. But the deep convection in the water-cloud layer around 10 bars, which is thought to be related to the giant storm, is much deeper than 2 bars. It is not clear how the solar heating is transported to the relatively deep layers, which needs further investigations.

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