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Saturn's visible lightning, its radio emissions, and the structure of the 2009–2011 lightning storms ☆

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ABSTRACT

Visible lightning on Saturn was first detected by the Cassini camera in 2009 at ∼35° South latitude. We report more lightning observations at ∼35° South later in 2009, and lightning in the 2010–2011 giant lightning storm at ∼35° North. The 2009 lightning is detected on the night side of Saturn in a broadband clear filter. The 2011 lightning is detected on the day side in blue wavelengths only. In other wavelengths the 2011 images lacked sensitivity to detect lightning, which leaves the lightning spectrum unknown.

The prominent clouds at the west edge, or the "head" of the 2010–2011 storm periodically spawn large anticyclones, which drift off to the east with a longitude spacing of 10–15° (∼10,000 km). The wavy boundary of the storm's envelope drifts with the anticyclones. The relative vorticity of the anticyclones ranges up to $-f/3$, where f is the planetary vorticity. The lightning occurs in the diagonal gaps between the large anticyclones. The vorticity of the gaps is cyclonic, and the atmosphere there is clear down to level of the deep clouds. In these respects, the diagonal gaps resemble the jovian belts, which are the principal sites of jovian lightning.

The size of the flash-illuminated cloud tops is similar to previous detections, with diameter ∼200 km. This suggests that all lightning on Saturn is generated at similar depths, ∼125–250 km below the cloud tops, probably in the water clouds. Optical energies of individual flashes for both southern storms and the giant storm range up to 8×10^9 J, which is larger than the previous 2009 equinox estimate of 1.7×10^9 J. Cassini radio measurements at 1–16 MHz suggest that, assuming lightning radio emissions range up to 10 GHz, lightning radio energies are of the same order of magnitude as the optical energies.

Southern storms flash at a rate ∼1–2 per minute. The 2011 storm flashes hundreds of times more often, ∼5 times per second, and produces $\sim 10^{10}$ W of optical power. Based on this power, the storm's total convective power is of the order 10^{17} W, which is uncertain by at least an order of magnitude, and probably is underestimated. This power is similar to Saturn's global internal power radiated to space. It suggests that storms like the 2010–2011 giant storm are important players in Saturn's cooling and thermal evolution.

1. Introduction

Lightning on Saturn was first, controversially, detected by the Voyagers as radio emissions called Saturn Electrostatic Discharges, or SEDs (Burns et al., 1983; Kaiser et al., 1983; Yair et al., 2008). The lightning origin of SEDs was later confirmed by Cassini using correlation of SEDs with convective-looking clouds in the images (Porco et al., 2005; Fischer et al., 2007; Dyudina et al., 2007). The first direct observation of lightning flashes in Cassini night side images was taken during Saturn's 2009 equinox (Dyudina et al., 2010). Equinox geometry minimizes ring light illuminating Saturn's clouds, which is the main obstacle for lightning detection. The lightning flashes were detected at planetocentric latitudes of ∼−35°, where most of the lightning storm clouds were seen, and where the SEDs were observed by Cassini since its arrival at Saturn in 2004. These thunderstorms occurred one at a time, lasting for days to months, and had months to years of lightning-free gaps in between (Fischer et al., 2011b). The optical lightning observations at equinox were luckily taken during an active storm, the longest of the detected thunderstorms, which lasted from mid-January to mid-December 2009.

This paper reports on new detections of visible lightning by the Cassini camera obtained after the equinox. This includes more

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flashes detected in the 2009 storm and the flashes in the sunlit clouds of the 2010–2011 north hemisphere's giant storm. The 2010–2011 detection is the first observation of lightning on the day side of any planet other than the Earth. The 2010–2011 giant storm (Fischer et al., 2011a; Sánchez-Lavega et al., 2011; Fletcher et al., 2011; Sayanagi et al., 2013; Laraia et al., 2013; Janssen et al., 2013; García-Melendo et al., 2013) is much larger than the 2004–2009 southern storms and is usually classified as one of the Great White Spots, which are planet-encircling storms that occur about once every Saturn's year (29.5 Earth years) (Sánchez-Lavega et al., 2011). In this paper we give new estimates of the energies, rates, and location of Saturn's lightning, related structure and dynamics of the storms, and relations between visible lightning and SEDs.

Section 2 shows how the new lightning observations, detecting Saturn's lightning on the cloud background for the first time, reveal the exact location of lightning within the cloud. We derive wind vectors, vorticity, and cloud heights of the 2010–2011 storm on February 26 2011, at the time of the lightning observations. Also we relate lightning to cloud motions. In Section 3 we infer the vertical location (depth) of lightning using the observed lightning spot size. Section 4 reports timing of the flashes on timescales down to the fraction of a second and their relation to SEDs. Section 5 presents energies and flash rates of lightning, their statistical relation with SEDs, power produced by the 2010–2011 giant storm and its importance for Saturn's thermal evolution. Section 6 discusses why the detection of visible lightning in blue-filtered images and not in other wavelengths cannot be used to infer the lightning color. In other words, we cannot say that the lightning is blue. We discuss the relation of clouds to lightning, and the detectability of lightning by radio and imaging on the day and night sides of Saturn in Section 7.

Some additional details on the lightning flash data, and the techniques used for lightning detection and wind measurement are described in the Appendix A.

2. Lightning geometry and cloud motion

Optical lightning was first detected on the night side of Saturn during the August 2009 equinox (Dyudina et al., 2010). At equinox the ring illumination of Saturn was minimal, and the clouds were not seen. Over 12 min of observations, the lightning flashes were consistent with a single location at $-36.4° \pm 0.1°$ planetocentric latitude producing flashes about once a minute. We will use planetocentric latitudes for the rest of the paper.

Fig. 1 shows another night side detection in 2009, also at about $-35°$ latitude, with lightning flashes in a cloud illuminated by Saturn's rings. Unlike the single-location equinox observations, during the 16 min of observation this storm flashes at least in two locations. The exposure times of the images in Fig. 1 alternate between 120 s and 15 s (see also Table A1 of the Appendix A). The two different exposure levels can be distinguished by the smear of the cloud boundaries induced by Saturn's rotation in 120-s exposures. From the five 15-s exposures (total 75 s), two showing lightning, we infer a rate of 1–2 flashes per minute. Accordingly, 2–4 such flashes would be expected during each of the 120-s exposures. They are hard to identify. Most likely those flashes are seen in each of the long-exposure images as faint spots not substantially exceeding the background brightness (which accumulates with exposure length). In addition, there are three bright flashes in the 120-s frames 4 and 8. These flashes have round shapes in map projection, are not smeared, and therefore are probably bright single flashes that occur rarely (see timing discussion in Section 4).

Fig. 2 shows locations of the flashes seen on Saturn's day side in the giant storm on February 26 2011. The background false-color map shows clouds at different depths by different colors: blue indicates upper haze, green – intermediate clouds, red – deep clouds, and white – optically thick clouds reaching the upper levels of the atmosphere.

Several locations of the storm flash repeatedly during the two Saturn days, i.e., flashes appear at nearly the same place in the two maps in Fig. 2. Lightning is most active near the head of the storm. Three flashes are detected there: two in the first map (double yellow × symbol), and one in the second map. Radio observations show that the head was producing most of the lightning throughout the storm's life (Fischer et al., 2011a; Sayanagi et al., 2013).

As predicted from the radio data in Fischer et al. (2011a), lightning occurred not just near the head, but also in other locations in the storm. SEDs were observed over an increasing longitudinal range as the storm grew, indicating lightning between the head and the large blue anticyclonic vortex at the right edge of Fig. 2). SED measurements show that at the end of February lightning flashes occurred over $\sim$80° of longitude eastward from the head. Optical flashes in Fig. 2 are spread over $\sim$70° in longitude. This is about 2/3 of the distance from the head to the vortex. The last 1/3 of the storm (longitudes 0° to 40° in Fig. 2) has a less turbulent appearance than the first 2/3. Possibly the weaker updrafts are manifested in less efficient charge generation and separation processes, which eventually lead to weaker electrical fields and fewer (or none at all) flashes.

Figs. 3–5 show the details of Fig. 2 at higher spatial resolution (see Online Supplemental Data for even higher resolution versions), and velocity and vorticity maps. Our cloud-tracking technique for measuring velocity and vorticity and the uncertainties are described in detail in the Appendix A.

As one can see from Figs. 3–5, there are many regions with vorticity more negative than $-5 \times 10^{-5}\ s^{-1}$. These are large anticyclones, which dominate the flow field within the storm. The head itself is a large anticyclone, and it seems to shed anticyclones that drift off downstream to the east. The blue oval at longitudes 350–360° west (Fig. 5) is the first anticyclone; it was shed in December 2010, shortly after the storm appeared (Sánchez-Lavega et al., 2011; Sayanagi et al., 2013). The head sheds these anticyclones at a nearly constant rate, so the spacing between them remains roughly constant (Sayanagi et al., 2013) in the range 10–15° of longitude ($\sim$8500–13,000 km). The clouds that mark the northern edge of the storm have a wave-like appearance. The crests and troughs of the wave are associated with the anticyclones and move with them to the east, away from the source. The crests and troughs are not standing waves, like ship waves or waves behind boulders in a stream, whose phase speed matches that of their source. In other words, they are not simple Rossby waves propagating to the west with the head.

Strictly speaking, Figs. 3–5 show maps of relative vorticity ζ, the spin of fluid elements due to their motion relative to the planet. The largest negative values in the Saturn storm are probably about $-7 \times 10^{-5}\ s^{-1}$, although even larger values may have been obscured during smoothing of the vorticity map. The other element of vorticity is the planetary vorticity f, which arises due to the rotation of the planet. At the latitude of the storm, this planetary vorticity $f = 2\Omega sin\,\phi_g$ is $20 \times 10^{-5}\ s^{-1}$, where ϕ_g is planetographic latitude. Thus the relative vorticity is of order $-f/3$, which is 1/3 of the limiting value $-f$ of an anticyclone under gradient wind balance (Salby, 1996; Holton, 2004). Fluid elements emerge from the adiabatic fluid interior of the planet with zero values of Ertel's potential vorticity Q, since Q is proportional to the gradient of potential temperature and that is zero for an adiabatic region (Salby, 1996; Holton, 2004). As they emerge into the stably stratified troposphere, the fluid elements still have $Q \approx 0$, because Q is a conserved quantity, but they accomplish this by