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Detection of visible lightning on Saturn

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[1] Until now, evidence for lightning on Saturn has been indirect – through radio emissions and cloud morphology. Here we report the first visible detection of lightning, on the night side on August 17, 2009 at −36.4° ± 0.1° planetocentric latitude and 10.6° ± 0.9° west longitude. No other locations produced lightning detectable by either imaging or radio. The lightning images are consistent with a single cloud flashing once per minute. The visible energy of a single flash is comparable to that on Earth and Jupiter, and ranges up to 1.7×10^9 Joules. The diameter of the lightning flashes is ~200 km, which suggests the lightning is 125–250 km below cloud tops. This depth is above the base of the liquid H_2O-NH_3 cloud and may be either in the NH_4SH cloud or in the H_2O ice cloud. Saturn's lower internal heat transport and likely 5–10 fold enrichment of water largely explain the lower occurrence rate of moist convection on Saturn relative to Jupiter.

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1. Introduction

[2] Existence of lightning on Saturn had been discussed since Voyager times as an explanation for radio emissions called Saturn Electrostatic Discharges, or SEDs [*Burns et al.*, 1983; *Kaiser et al.*, 1983; *Yair et al.*, 2008]. Cassini data showed that SED activity is correlated with convective-looking clouds on the side of Saturn that faces the spacecraft [*Porco et al.*, 2005; *Fischer et al.*, 2007; *Dyudina et al.*, 2007]. However, no one had seen lightning flashes on Saturn directly until now. Except at equinox, the rings make the night side of Saturn brighter than Earth under a full moon, so it has been impossible to distinguish clouds illuminated from below by lightning and clouds illuminated from above by ring shine. For more discussion of visible lightning searches on Saturn, see the auxiliary material.[6]

2. Results

[3] Figure 1 shows diffuse spots on the night side of Saturn produced by lightning. They were observed during one of the darkest nights on Saturn, six days after the August 11, 2009 Saturn equinox from a distance of 35.5 Saturn radii. Saturn's rotation during the 3-minute exposures caused points fixed in longitude (such as lightning storms) to move from left to right by ~1.69°, the distance equal to the spacing between the two solid vertical lines in Figure 1. The flashes occur at random times during the exposures and appear as nearly circular diffuse spots on the map. The fact that all the flashes fall between the two vertical lines and are at the same latitude says that the flashes could be emerging from the same point on the planet. The last image, where the points are spread out between the two vertical lines, restricts the longitude of this point to a narrow range, 10.6° ± 0.2° west longitude. If the flashes are from the same point, the position of each flash indicates the time that it occurred. These times are plotted in Figure 2, middle plot, starting with the beginning of the first exposure. The gaps between the images correspond to the 20-second periods when the camera was not observing. Visible flashes occur about once a minute (nine flashes per 12 minutes of total exposure time). The ordinate of the middle plot in Figure 2 shows the energies emitted by the individual flashes in the wavelength band 200–1100 nm. The diffuse appearance of the flashes indicates that the clouds above the lightning have sufficient optical thickness, i.e., greater than ~5, to block the direct light from the lightning bolt [*Dyudina et al.*, 2002].

[4] Following lightning energy estimates for Jupiter by *Little et al.* [1999] and *Dyudina et al.* [2004], we treat the observed flashes as if they were patches of light at the cloud tops emitting isotropically up and down. Optical energies for Saturn range up to 1.7×10^9 J, which is comparable to Jupiter energies of $(0.21–15.7) \times 10^9$ J [*Little et al.*, 1999]. These estimates are lower bounds, since they do not take into account absorption within the clouds. They are comparable to the largest terrestrial flashes [*Turman*, 1977; *Borucki et al.*, 1982], which are 5×10^9 J, although the median terrestrial lightning is orders of magnitude smaller [*Kirkland et al.*, 2001]. The same may be true of lightning on Saturn, because flashes fainter than 1×10^8 J are below the camera's detection limit. According to the laboratory

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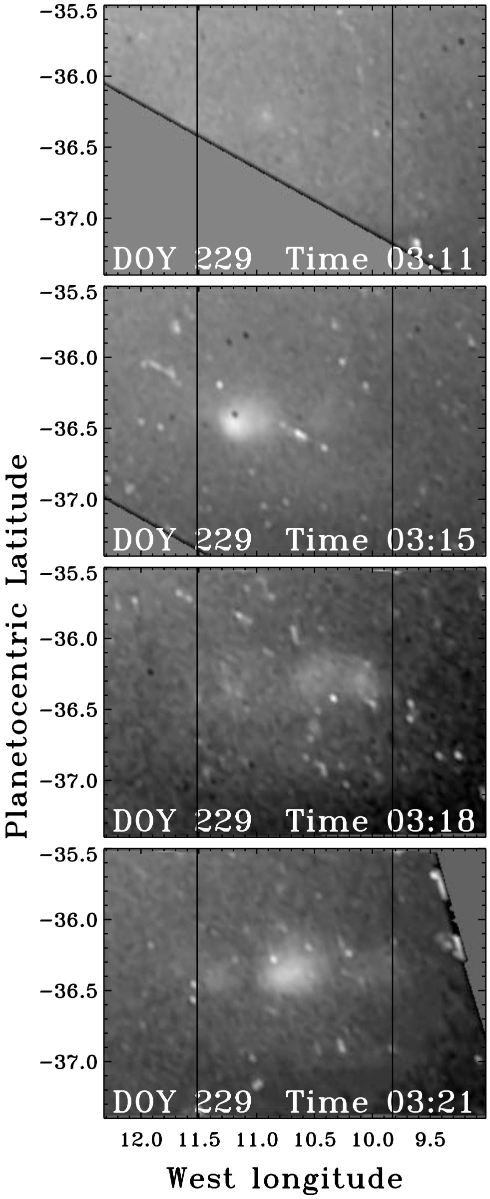

Figure 1. A map-projected sequence of four night side images taken over a 780 second period on day of year (DOY) 229, which is August 17, 2009, with the broadband visible filter [*Porco et al.*, 2004]. The first frame is at the top (see the time labeled in the images). The frames are marked with latitude, longitude, and time at the middle of the exposure. The maps are scaled such that the distances in km are the same in the latitudinal and longitudinal directions. The grey-colored corners of frames 1, 2, and 4 are missing data not covered by the images. Each frame is a three-minute exposure with a 20-second gap between the end of one exposure and the beginning of the next. The diffuse spots of size 0.5° and latitude −36.4° are lightning. Such spots are visible in all four frames. The smaller bright spots are caused by cosmic rays hitting the detector. Saturn's rotation during the exposures caused points fixed in longitude to move from left to right by a distance equal to the spacing between the two solid vertical lines. Flashes separated by shorter times appear closer in longitude.

simulations [*Borucki and McKay*, 1987], the total energy dissipated by lightning is 10^3 times the optical energy.

[5] We estimate the storm's average power in visible light by dividing the sum of the individual flash energies by the total exposure time of 12 minutes. The result, $1 \pm 0.2 \times 10^8$ W, is about ten times weaker than the strongest storm seen on Jupiter by Galileo [*Little et al.*, 1999]. The storm on Jupiter was flashing about every 5 seconds. The storm on Saturn flashes at 1/10 of this rate.

[6] Figure 2 (bottom) compares the times of the SEDs, as detected by the Cassini Radio and Plasma Wave Science (RPWS) instrument [*Fischer et al.*, 2008], to the times of the visible lightning, assuming the visible flashes are all from the same point on the planet. The RPWS instrument scans in radio frequency and detects only about 1/3 of the SEDs. This gives the true SED rate of 3 × (3 SED/780s) ~1 SED/min, the same as the visible flash rate. The camera detects all the visible flashes when the shutter is open. However, the strongest SED, which is at 325 s, has no visible flash, assuming the weak SED at 300 s belongs with the weak flash at about the same time. Either the light from the strong SED is absorbed by a thick cloud that was not covering the other flashes, or else the strong SED belongs to the strong flash plotted at 240 s, whose time is mislabeled because it comes from a source to the west of the main source. The latter explanation is favored because it reconciles the energy and timing of the visible flashes with those of the radio emissions.

[7] Figure 3a shows a portion of the map-projected day side image taken 2.5 hours before the lightning. This image was taken with Cassini's wide-angle camera, so the resolution is 10 times poorer than the night side images of Figure 1, which were taken with the narrow-angle camera. The storm has several bright clouds within it. Lightning from the night side matches the location of one of these clouds. In the present survey, which covers 30% of the surface, no lightning is seen at any other cloud (see auxiliary material). Lightning on Jupiter often but not always matches dayside clouds [*Gierasch et al.*, 2000; *Dyudina et al.*, 2004; *Borucki and Magalhães*, 1992]. All the SED-producing clouds during the 5 years of the Cassini mission have been at the same latitude of −35° [*Dyudina et al.*, 2007].

[8] The present lightning storm has been active at radio wavelengths for 9 months, from January to October 2009. Figure 3b shows the same storm as in Figure 3a, but a month earlier and in better resolution. The storm's general appearance is similar to the lightning storms observed in 2004 and 2006 [*Dyudina et al.*, 2007]. The 2004 storm (see Figure S1) produced 2000-km-scale plumes of bright material on a timescale less than a day, consistent with a modeled convective updraft [*Hueso and Sánchez-Lavega*, 2004]. The plumes fade with time and evolve into dark ovals. The ovals are probably dark due to materials produced by lightning [*Podolak and Bar-Nun*, 1988; *Baines et al.*, 2009]. In Figure 3b there is a bright cloud at about 2–3° west longitude and −32.5° latitude. This cloud looks similar to the cloud with lightning in the upper panel, and to the 2004 plumes. By analogy to the 2004 storm, this cloud is likely the center of convection and therefore lightning.

[9] The size of the diffuse flashes indicates the depth of the lightning below the cloud tops. Figure 4 shows how brightness falls off with distance from flash center for the two brightest flashes. The half width at half maximum (HWHM) for these flashes is about 100 km. A light scattering model

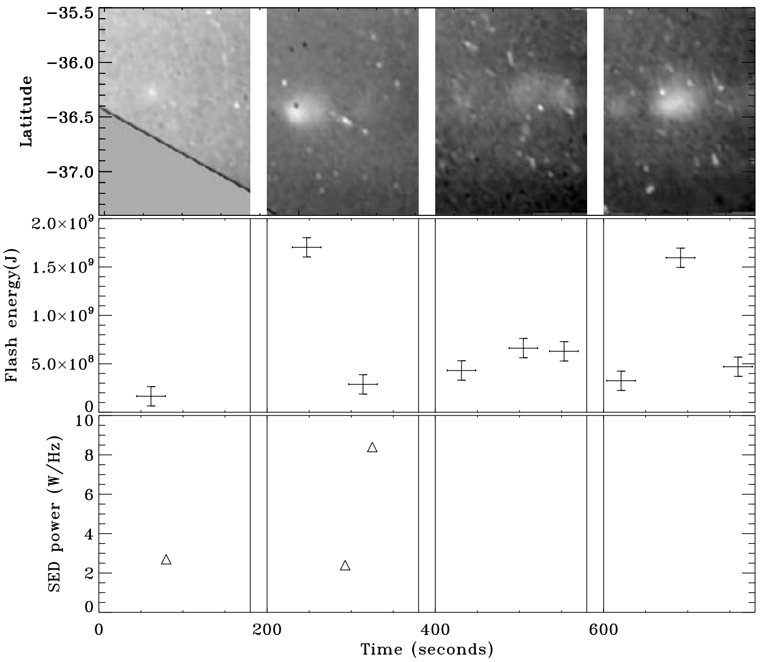

Figure 2. Energy of individual flashes versus time from the start of the first image (Day 229, 2009, at 3h 10m 29s) compared to the SED spectral source power, which is a distance-independent measure of the SED strength calculated from the incident radio flux assuming isotropic radiation from the source [*Fischer et al.*, 2006]. The upper panels show map-projected images. The middle panels show flash energy. Times are assigned by assuming all the flashes are from a single source. The bottom panels show SED spectral power at the times measured by the RPWS instrument. Saturn's rotation carries the lightning source from left to right during each 180-second exposure. The gaps between the images indicate the times when the camera was not observing. The uncertainty in time for each flash is given by the range of possible source longitudes that allows all the flashes from the four images to fit within the corresponding exposure windows.

by *Dyudina et al.* [2002] suggests that the depth of the point-sized lightning below the cloud tops is 1.25–2.5 times the HWHM, depending on the cloud structure. This gives an estimate of 125–250 km for the depth of lightning measured from the tops of the clouds.

[10] The depths of the clouds depend on composition, in particular the abundance ratios N/H, S/H, and O/H relative to solar values. For 5 × solar [*Lindal et al.*, 1985; *Atreya and Wong*, 2005; *Atreya*, 1986] (see auxiliary material), the four clouds and their base depths measured downward from the 100 mbar level are: NH_3 (129 km), NH_4SH (220 km), H_2O ice (270 km), and H_2O/NH_3 solution (364 km). For lower abundance ratios, the base depths are shallower, *i.e.*, higher in the atmosphere. The cloud tops could be as shallow as 150 mbar (13 km) in areas of moist convection [*Hueso and Sánchez-Lavega*, 2004] or as deep as 1 bar (90 km), which is the average depth of the NH_3 cloud top [*West et al.*, 2009]. For the 5 × solar case, if the cloud tops and lightning depths are shallow - 13 km and 125 km, respectively - the optical flashes could be in the NH_4SH cloud. If the cloud tops and lightning depths are deep - 90 km and 250 km, respectively - the optical flashes could be in the solution clouds. The flashes could also be in the H_2O ice cloud, which would be consistent with terrestrial lightning [*MacGorman and Rust*, 1998].

3. Discussion

[11] The lightning storm on Saturn seems to be unique (see auxiliary material). In contrast, the Galileo imaging system detected 20 lightning storms on Jupiter in a sequence

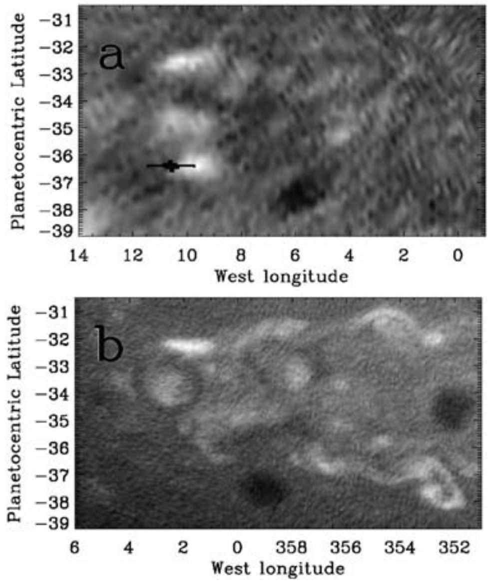

Figure 3. (a) A map-projected day side image taken with the continuum filter CB2 [*Porco et al.*, 2004] on day 229, 2009, at 0h 50m. A point with error bars indicates the location of the nightside flashes. Longitudinal error bars are shown for the assumption of a single source (thick horizontal error bar) and for multiple sources (thin error bar). (b) A better resolved map-projected image of the same storm a month before the lightning observation, on day 198, 2009, at 9h 48m. The image was taken with clear filter combination CL1 and CL2 by the wide angle camera.

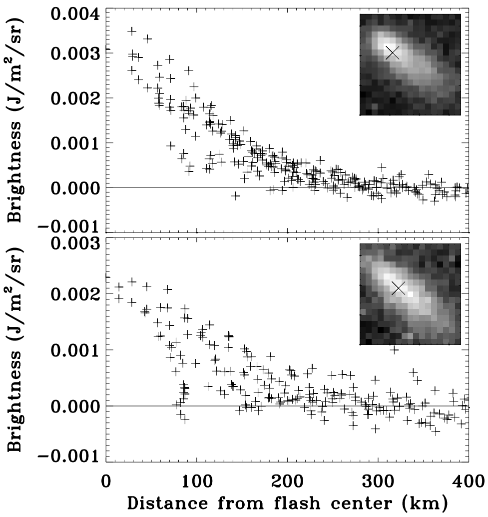

Figure 4. Brightness distribution in the two brightest flashes versus distance from the flash center measured along Saturn's surface. The background brightness was subtracted from the image, which resulted in a mixture of positive and negative brightness values. The insets in the right top of each plot show the unprojected image of the corresponding flash where the flashes are foreshortened due to slant viewing. The × symbol indicates the assumed flash center.

that covered about one-half of the planet [*Little et al.*, 1999]. Two factors might be contributing to this difference. First, Saturn's lower internal heat flux means that moist convection is less frequent on Saturn, since moist convection is the principal mode of vertical heat transport [*Salby*, 1996] and also the principal mode of electrical charge separation [*Gierasch et al.*, 2000; *Saunders*, 2008]. Second, Saturn may have a 5–10 fold enrichment of water relative to solar composition, in analogy with the 5–10 fold enrichment of methane [*Fletcher et al.*, 2009]. Although Jupiter's water abundance is controversial, the enrichment factors for methane and other gases are in the range 2.5–3.5 [*Taylor et al.*, 2004; *Atreya and Wong*, 2005]. This means that Saturn probably has more heat capacity, as latent heat of water, and greater ability to carry the heat, which requires fewer moist convective storms. Further, if the lightning flashes on Saturn are at higher atmospheric densities, where the breakdown voltage is higher [*Yair et al.*, 1995], then the Saturn flashes might be less frequent and more energetic than those on Jupiter. Outstanding questions are: Why have all the Cassini storms been at one latitude −35° while the SEDs of the Voyager era suggest equatorial lightning? Does the latitude change with the seasons (Voyager data are from northern spring, Cassini data are from northern winter)? What do the storms reveal about the deep cloud structure and water abundance? How important are these storms in bringing internal heat to the surface of the planet? These questions stress the need for additional lightning searches on Saturn, and are also applicable to other planetary atmospheres where lightning surveys are planned for future spacecraft.

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