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A giant thunderstorm on Saturn

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Lightning discharges in Saturn's atmosphere emit radio waves[1] with intensities about 10,000 times stronger than those of their terrestrial counterparts[2]. These radio waves are the characteristic features of lightning from thunderstorms on Saturn, which last for days to months[2]. Convective storms about 2,000 kilometres in size have been observed in recent years at planetocentric latitude 35° south[3–5] (corresponding to a planetographic latitude of 41° south). Here we report observations of a giant thunderstorm at planetocentric latitude 35° north that reached a latitudinal extension of 10,000 kilometres—comparable in size to a 'Great White Spot'[6,7]—about three weeks after it started in early December 2010. The visible plume consists of high-altitude clouds that overshoot the outermost ammonia cloud layer owing to strong vertical convection, as is typical for thunderstorms. The flash rates of this storm are about an order of magnitude higher than previous ones, and peak rates larger than ten per second were recorded. This main storm developed an elongated eastward tail with additional but weaker storm cells that wrapped around the whole planet by February 2011. Unlike storms on Earth, the total power of this storm is comparable to Saturn's total emitted power. The appearance of such storms in the northern hemisphere could be related to the change of seasons[7], given that Saturn experienced vernal equinox in August 2009.

On 5 December 2010, the Radio and Plasma Wave Science (RPWS) instrument[8] on board the Saturn-orbiting Cassini spacecraft detected radio emissions associated with a new lightning storm. On the same day, the Cassini Imaging Science Subsystem (ISS)[9] observed a bright cloud, 1,300 km × 2,500 km in size, at planetocentric latitude 32° N and longitude 245° W (here we use the Voyager Saturn Longitude System, SLS, corresponding to a rotation period of 10 h 39 min 22 s). The storm might have started somewhat earlier, as there is a gap in observations of about 2 days before the detection in the RPWS data.

The radio waves emitted by lightning discharges in Saturn's atmosphere are known as Saturn electrostatic discharges[1], SEDs, and are usually observed as short individual radio bursts, but in this event (see the time–frequency spectrogram of Fig. 1) they cluster to an almost continuous emission owing to the high flash rate. On their way to Cassini's radio receiver the SEDs must pass through Saturn's ionosphere, and therefore the low-frequency extent of the emission can be used as a measure of the peak electron plasma frequency of the intervening plasma[10]. The decreasing low-frequency cut-off in Fig. 1 is consistent with a storm rotating with the planet from the dayside to the nightside, where electron densities of the ionosphere are lower. Such measurements by the Voyager and Cassini spacecraft have yielded typical peak electron densities somewhat larger than $10^5\,\mathrm{cm}^{-3}$ around noon, but nightside densities as low as 10^2–$10^3\,\mathrm{cm}^{-3}$ (derived from the Voyager SEDs[10]) have not so far been observed by Cassini[11]. Averaged day/night variations in electron density observed by Cassini were less than two orders of magnitude[11]. Models taking into account an influx of water from Saturn's rings can reproduce the electron densities at dusk and dawn, but most models cannot reproduce the large day/night variation; this is because of the long-lived H^+ ion in Saturn's ionosphere[11–13].

Viewed from Cassini, SEDs occur in episodes, and start or stop at the time when the visible storm enters or leaves the radio horizon. This consistency in longitudes enables an association of SEDs with storm clouds. Further confirmation of such a link comes from a drift rate of the storm cloud consistent with the SED episode recurrence period, and a correlation between cloud brightness and SED rates[4,5]. Figure 2 shows the episodic SED activity, which was comparable to previous SED storms in the first days of the storm and reached unprecedented levels on 12 December. The real flash rate is unknown, as we do not know how many SEDs would appear very close to the source. The lower limit of the peak flash rate is ~10 SEDs per second.

The polarization of SEDs for this storm at frequencies below 2 MHz is strongly left-hand circularly polarized, which is opposite to the SED polarization from southern hemisphere storms[14]. This difference is related to the opposite direction of the magnetic field in the two hemispheres relative to the radio wave propagation vector, as the field is

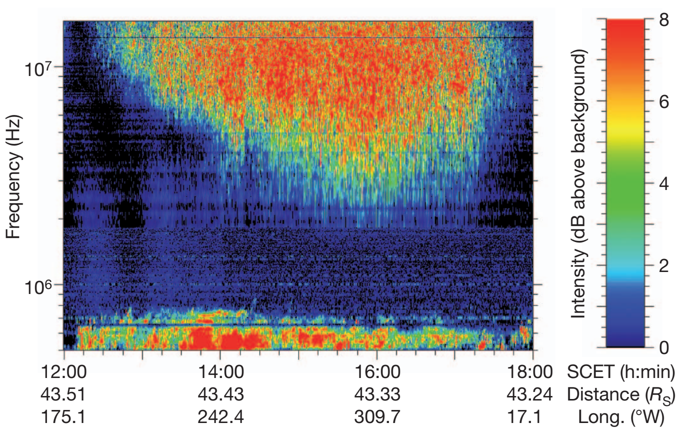

Figure 1 | Time-frequency spectrogram of the SED episode on 12 December 2010. The colour-coded intensity (with 30% background division) of the radio emissions is plotted as a function of spacecraft event time (SCET) over 6 h and frequency from 500 kHz to 16 MHz on a logarithmic scale. Cassini coordinates (distance to Saturn's centre in units of Saturn's radius, R_S, and SLS west longitude in degrees, 'Long.') are indicated on the abscissa. Cassini was in the equatorial plane at a local time of ~18.6 h. The RPWS instrument sweeps in frequency, and it detects the broadband SEDs at whatever frequency (above the ionospheric cut-off) it happens to be tuned to at the time of the flash. This SED episode shows such a high flash rate that the receiver sweep rate of ~28 frequency channels per second (35.2 ms per channel) can no longer resolve the single SEDs. Flash rates of 5–10 SEDs per second can lead to a temporal superposition of SEDs that normally extend over several frequency channels. At the edges of the episode, where the rate is lower, one can see the individual SED bursts. The continuous emission below 800 kHz is Saturn kilometric radiation.

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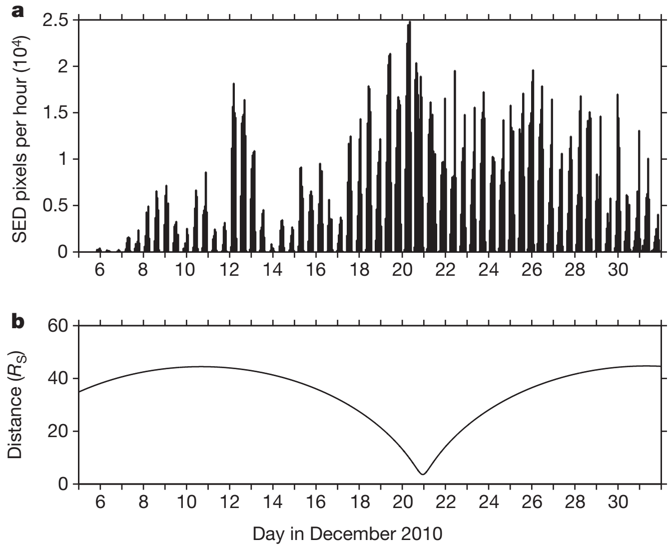

Figure 2 | Saturn's lightning activity and Cassini's distance to Saturn as a function of time for December 2010. **a**, The number of SED pixels as a function of day in December 2010. Owing to the high flash rates, the single SEDs sometimes cannot be counted. Instead, we give the number of SED pixels, which is the same as the number of single time–frequency measurements. Previous lightning storms from 35° S (ref. 5) showed SED numbers more than an order of magnitude smaller for similar distances. **b**, The distance of Cassini to Saturn's centre in units of Saturn radii (R_S); these data help interpretation of **a**, as the signal intensities of SEDs decrease with distance squared. The peak in SED numbers on 20/21 December coincides with Cassini's closest approach to Saturn.

axisymmetric. SED-related storms were much more common in the years around Saturn's equinox. From November 2007 until now (May 2011) they were present for ~69% of the time, which is about 10 times more compared to the first years of Cassini's orbit around Saturn.

On 5 December the storm was located at latitude ~32° N, where the wind speed with respect to the Voyager SLS is nearly zero. In

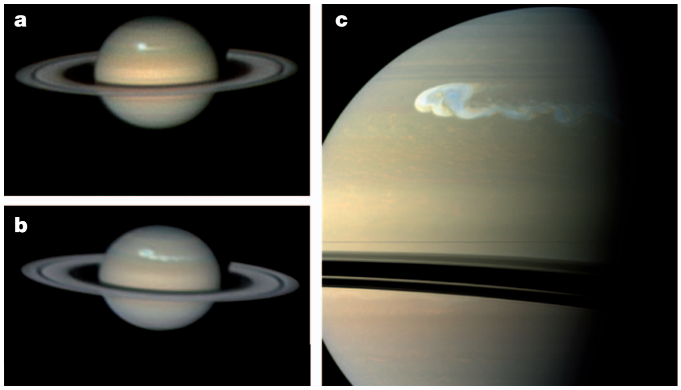

Figure 3 | Images of Saturn with the storm. **a**, Image taken on 13 December 2010 with an 11-inch Schmidt-Cassegrain telescope in the Philippines (by C.G.). The centre of the storm was located at longitude ~262° W and latitude ~34° N. At that time, the latitudinal size of the storm had already grown from 1,300 km to ~6,800 km (~7°). **b**, Image taken on 22 December 2010 with a 16-inch Newtonian telescope in Australia (by A.W.). It shows that the plume had grown to a latitudinal and longitudinal extent of ~9,000 km and ~15,000 km, respectively. The centre was at longitude ~283° W. **c**, Image taken on 24 December 2010 with the wide-angle camera of Cassini. Here the storm's latitudinal and longitudinal extent is ~10,000 km and ~17,000 km, respectively, with an eastward tail that extends much further. The storm centre was at longitude ~288° W. Image credits: C.G., A.W., NASA/JPL/SSI.

the interval from 5 to 8 December, the SEDs were observed at nearly constant sub-spacecraft west longitudes, indicating no drift. However, the images after 8 December showed that the core region of the storm had moved to a latitude of 34° N, where the wind speed has a local minimum around $-22\ \mathrm{m\,s^{-1}}$ (corresponding to a westward drift of ~2.3° per Earth day) and is therefore the centre of a westward jet[7,15]. From the Earth-based images of December and early January, we derived a westward drift of 2.4° ± 0.1° per day for the approximate centre of the storm. In the Cassini images, the western edge showed a higher drift of 2.8° ± 0.1° per day. All images in Fig. 3 show a storm with a head on its western side and a tail to the east. As the head moves

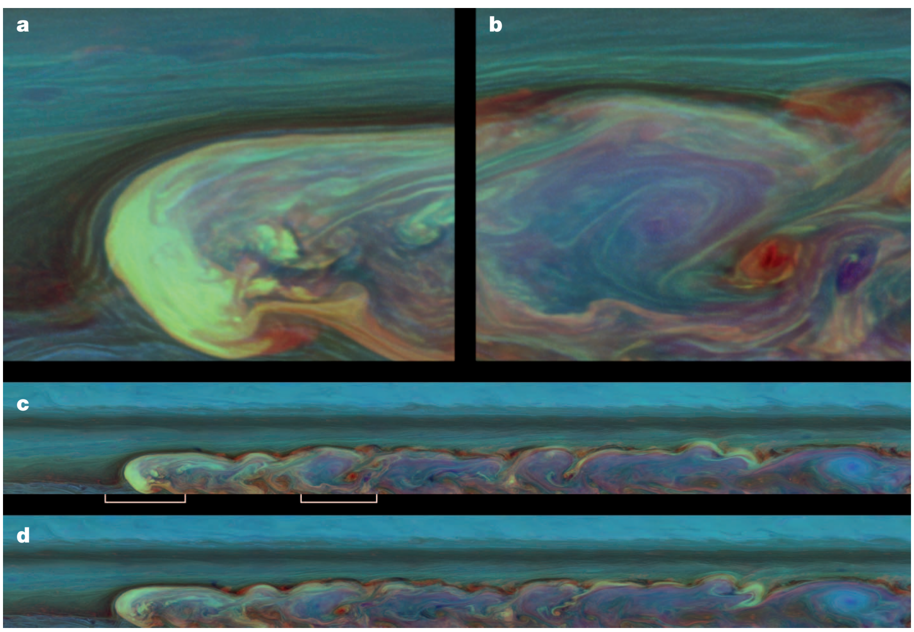

Figure 4 | False-colour views showing the height of the storm clouds. Images with three filters sensitive to different amounts of absorption by methane gas were superposed to make these colour mosaics. The filtered image at 889 nm is projected as blue, and sees only the highest clouds. The filtered image at 727 nm is projected as green, and sees high and intermediate clouds but not the lowest clouds. The filtered image at 750 nm is projected as red, and sees clouds at all levels. **a**, **b**, Magnified views at full resolution of the areas indicated by white brackets in **c**. **d**, Image showing the storm ~11 h after image **c** was taken. The images were taken by Cassini's narrow angle camera on 26 February 2011 from a distance of 2.4×10^6 km. Image credit: NASA/JPL/SSI.

with the westward jet, the relative flow at lower latitudes is eastward, which accounts for the eastward tail to the south of the storm. The head plus tail had a longitudinal extent of $\sim 90^{\circ}$ in the late December images, and the disturbance was wrapped around the planet by February. The RPWS instrument occasionally observed SEDs over an extended longitude range. This suggests at least one small and temporarily active SED storm cell in the tail, whereas the main lightning activity took place in the head of the storm. Figure 4 shows Cassini high-resolution views of the storm in filters that bring out differences in cloud heights. Yellows and white identify optically thick clouds at high altitudes located mostly around the head of the storm.

Saturn's lightning storms are thought to be located in the water cloud layer at pressure levels around 8–10 bar (ref. 2). Optical flash observations around Saturn's vernal equinox in August 2009 have restricted the flash depth to 125–250 km below the upper cloud layer[16]. As most of the sunlight is absorbed around the 1-bar level[17], the lightning storms are probably driven by internal heat. Moist convective plumes[18] transport particles from the ammonia and ammonium hydrosulphide clouds, as well as particles produced by the lightning itself, to levels above 1 bar (ref. 19). We estimate the contribution of the current storm to Saturn's emitted power using the accumulated outflow volume of the storm's anvil cloud. Assuming the molar mixing ratio of the water vapour in the plume before it rises is five times the solar value[20] ($O/H = 0.513 \times 10^{-3}$), condensation of all water would produce a temperature increase of 7.7 K. This temperature change would raise the power radiated at the latitude of the storm by 36%. Variations of this magnitude have occurred in the past. For instance, from 2004 to 2009, the emitted power was on average 17% higher in the southern hemisphere than in the northern hemisphere[21]. We assume the heated layer is 1 bar thick ($\sim 10^4\,\mathrm{kg\,m^{-2}}$), because that is the depth of the clouds we are seeing. Then it would take 6–10 years to radiate away the 7.7 K temperature rise. The excess energy in such a layer, if it were 10,000 km wide and $\sim 360^{\circ}$ in longitude, would be comparable to the total internal heat radiated by the planet in a year, assuming the internal power is (0.78/1.78) times the total radiated power[22]. Thus giant storms like this might be a significant term in the internal heat budget of the planet.

The switch in hemisphere of the lightning storms could be related to the change of seasons[7,23]. On Saturn, the seasonal effect is exaggerated by the shadow of the rings. The last SED storm in the southern hemisphere ended in mid-July 2010, $\sim$11 months after equinox, and this first storm in the northern hemisphere started $\sim$16 months after equinox. Convective storms around 35° N were imaged shortly after northern vernal equinox by the cameras of Voyager 1 and 2[24,25]. SEDs were also present at those times, but they were thought to be related to an equatorial thunderstorm[26,27]. There are similarities and differences between lightning storms on Saturn and on Earth. Saturnian thunderstorms last longer, are much larger, and occur only at very specific latitudes. SEDs are more intense than terrestrial flashes, but their duration is similar[2]. Charging mechanisms in the water clouds of Saturnian and terrestrial thunderstorms are probably similar, and lightning on Earth also has a seasonal dependence[28].

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Author Contributions G.F. analysed Cassini RPWS data and wrote the paper. W.S.K., D.A.G. and P.Z. helped in this analysis. U.A.D., A.P.I., S.P.E. and C.C.P. analysed the Cassini ISS image and calculated the energy of the storm. A.W. and C.G. imaged Saturn from the ground, and M.D. measured the size and drift of the storm from several images. All authors discussed the results and commented on the manuscript.

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