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Profuse activity of blue electrical discharges at the tops of thunderstorms

Olivier Chanrion[1], Torsten Neubert[1], Andreas Mogensen[1,2], Yoav Yair[3], Martin Stendel[4], Rajesh Singh[5], and Devendraa Siingh[6]

[1]National Space Institute (DTU Space), Technical University of Denmark, Lyngby, Denmark, [2]European Space Agency Technology Center, Noordwijk, Netherlands, [3]Interdisciplinary Center, Herzliya, Israel, [4]Danish Meteorological Institute, Copenhagen, Denmark, [5]KSK Geomagnetic Research Laboratory, Indian Institute of Geomagnetism, Allahabad, India, [6]Indian Institute of Tropical Meteorology, Pune, India

Key Points:
- The first results from the Thor experiment observing thunderstorms from the International Space Station are presented
- Profuse electrical activity reaching the lower stratosphere is observed at the top of thunderstorms
- The activity develops during the mature stage of a thunderstorm cloud development

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Movie S1

Correspondence to:
O. Chanrion,
chanrion@space.dtu.dk

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Abstract Thunderstorm clouds may reach the lower stratosphere, affecting the exchange of greenhouse gases between the troposphere and stratosphere. This region of the atmosphere is difficult to access experimentally, and our knowledge of the processes taking place here is incomplete. We recently recorded color video footage of thunderstorms over the Bay of Bengal from the International Space Station. The observations show a multitude of blue, kilometer-scale, discharges at the cloud top layer at ~18 km altitude and a pulsating blue discharge propagating into the stratosphere reaching ~40 km altitude. The emissions are related to the so-called blue jets, blue starters, and possibly pixies. The observations are the first of their kind and give a new perspective on the electrical activity at the top of tropical thunderstorms; further, they underscore that thunderstorm discharges directly perturb the chemistry of the stratosphere with possible implications for the Earth's radiation balance.

1. Introduction

The most notable element of a lightning discharge in the atmosphere is the bright channel of high ionization and enhanced electrical conductivity called a leader. Its propagation is not well understood but is thought to be mediated by a multitude of streamers emitted from the leader tip. The streamers are ionization waves that are difficult to observe because of their small spatial and temporal scales (mm-cm, ns) and their low luminosity relative to the leader. Our understanding of this energetic plasma process comes primarily from laboratory experiments [e.g., *Raizer and Allen*, 1997] and simulations [e.g., *Ebert et al.*, 2010]. However, the temporal and spatial scales increase with decreasing atmospheric density [*Pasko et al.*, 1998; *Ebert et al.*, 2006] and are larger by orders of magnitude in the stratosphere and mesosphere, which makes their study possible with today's imaging instruments [*Stenbaek-Nielsen et al.*, 2013].

The first scientific report of a discharge in the mesosphere, the red sprite in 1990 [*Franz et al.*, 1990], spurred research groups worldwide to point cameras above thunderstorms, leading to the discoveries of a multitude of other manifestations of electrical discharges such as the blue jet, blue starter (small blue jet), gigantic jet, and troll, collectively known as transient luminous events [*Wescott et al.*, 1996; *Lyons et al.*, 2000; *Lyons*, 2006; *Neubert et al.*, 2008; *Pasko et al.*, 2012; *Siingh et al.*, 2012]. It also inspired space scientists to turn their instruments toward the Earth to observe these events from the vantage point of space. The first dedicated instrument in space was the Imager of Sprites/Upper Atmospheric Lightning on the Taiwanese FORMOSAT-2 satellite launched in 2004, observing in a limb-viewing geometry [*Chen et al.*, 2003; *Kuo et al.*, 2015]. Cameras on the Space Shuttle orbiter also provided images over the years toward the limb [*Vaughan and Vonnegut*, 1989; *Yair et al.*, 2004] and on the International Space Station (ISS) toward the nadir [*Blanc et al.*, 2004; *Sato et al.*, 2015; *Jehl et al.*, 2013]. However, the finer details of the discharges are not well resolved in past space measurements because of large distances to the events (limb-viewing) or challenging viewing geometry (nadir-viewing).

In this paper, we present observations from the International Space Station (ISS) taken with a high-resolution and light-sensitive color camera pointed at an angle downward toward an active thunderstorm. The viewing geometry gives us close proximity to the storm good resolution in altitude. The observations were taken during the Thor experiment conducted by the first Danish astronaut on board the ISS and are the most spectacular of their kind because of the high level of discharge activity and of the unique combination

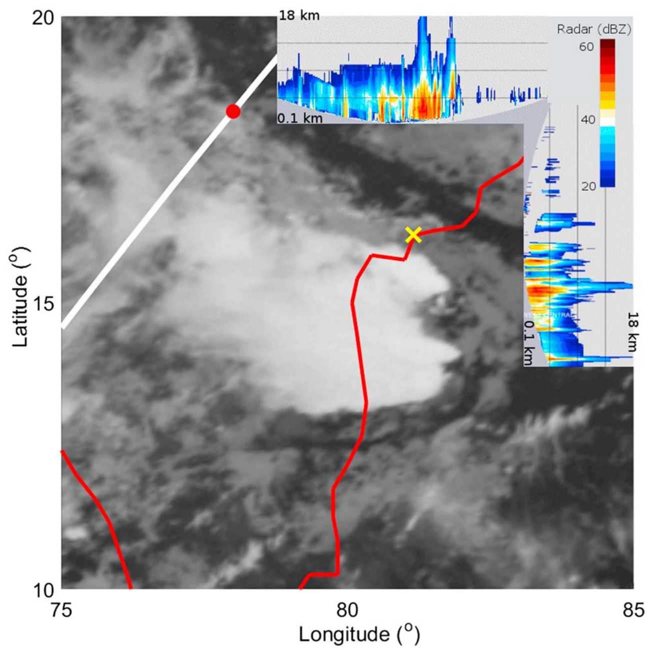

Figure 1. Meteosat infrared image of the cloud cover at 22:30 UTC with the ISS orbit (white track), its position at 22:21:20 UTC (red dot). The Machlipatnam (yellow cross) radar reflectivity vertical projections are shown on the two top-right plots as function of altitude at 22:21 UTC. (More detailed radar data are given on Figure S2.)

of viewing geometry and camera resolution. They reveal new aspects of discharge processes at cloud tops, including a pulsating blue jet and numerous kilometer-scale discharges.

2. The Thor Experiment

Named after the Nordic mythological god of thunder and lightning, the Thor experiment is designed to study processes at the top of thunderstorms and the atmosphere just above. The science objectives of the experiment are the formation of cloud turrets, the generation of high-altitude electrical processes, and generation of internal gravity waves from thunderstorm convection. In the experiment astronauts on the ISS image thunderstorms under conditions defined by the science team and the observations from the ISS are correlated data from other sources such as meteorological satellites and radars and ground-based lightning detection systems.

Thor was carried out for the first time from 2 to 11 September 2015, during the Iriss mission of Denmark's first astronaut, Andreas Mogensen. A science team on the ground forecasted thunderstorm activity up to 3 days in advance, predicting storm locations, observation time windows for ISS overflights, and camera pointing angles, and the information was uploaded to the ISS every 24 h. The forecasting procedure allowed mission schedulers to plan for several observation periods in the busy timeline of the astronaut. The measurements presented here were taken from the Cupola, a module underneath the ISS with a full view of the Earth.

The camera was a Nikon D4 set at 6400 ISO and recording 24 frames per second at 1920 × 1080 pixels, downscaled from 4928 × 2768 pixels of the sensor. It was mounted with a 58 mm/f1.2 lens, giving a 34.4° × 19.75° field of view corresponding to 1.07′/pixel. With these settings, the camera resolution was 130 m at nadir, 728 m at the limb, and 203 m for the discharge events pictured in Figures 3 and 4. Based on the ISO setting (giving the light level for minimum darkening) and assuming a linear response, we estimate the camera response to be 10 nW/bit. The data were recorded on a memory card and downloaded within a few hours to the supporting science team.

3. The Observations

The images are from a video of a thunderstorm over the eastern coast of India and the Bay of Bengal. It is 160 s in duration and is taken on the night of 8 September 2015, around 22:20 UTC (03:50 LT). The cloud cover of the region, as observed in the infrared band by the Meteosat satellite [*Schmetz et al.*, 2002] at 22:30 UTC, is shown in Figure 1 with the orbit of the ISS (northward bound) and its position at 22:21:30 UTC. The most active parts of the cloud are close to the eastern and leading edge of the cloud complex located at ~14°—16°N latitude and ~81°E longitude. Also shown are the position of the Machlipatnam Doppler weather radar at the edge of the storm system (16.18°N, 81.15°E) and data from the radar around the time of the observations.

The clouds viewed from the perspective of the ISS toward the southeast are shown in Figure 2. Illuminated by lightning inside the clouds, their three-dimensional structure becomes visible, with two sections reaching high altitudes of 15–18 km, typical of deep tropical convection. The right and larger section corresponds to the south-eastern region of the cloud complex, and the left section to the north-eastern region. As the ISS

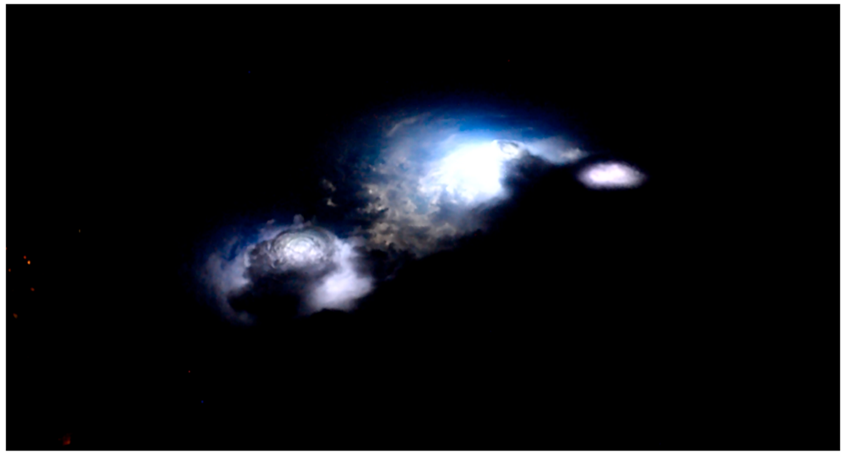

Figure 2. The two active regions of the clouds illuminated by lightning observed from the ISS.

passed over India, the cloud structure was seen from a range of viewing angles, confirming the structure apparent in Figure 2. The southern cloud had fewer and more powerful lightning flashes, one of which generated a sprite, while the northern cloud had higher lightning activity but with less apparent power as inferred from the optical emissions. It is from this latter region that the blue discharges were observed.

We first present observations of a pulsating blue jet. Figure 3 shows eight consecutive images beginning with the cloud illuminated by lightning deeper inside the cloud. The first pulse reaches a length of ~13.25 km (53 pixels) (2) after which it fades, leaving faint emissions up to ~17.5 km (70 pixels) (3). Then a second pulse appears at the base of the original discharge, with faint emissions reaching even higher to 10.5–20 km (42–80 pixels); these are disconnected from the activity at the root and may be the remains of the first pulse (4). The discharge then fades, with blue emissions remaining at the top (5). The discharge finally rebrightens a third time to 18.5 km (6), reaching its maximum extent of ~21.5 km (86 pixels) (7–8) before fading completely. The altitude and size of events have been calculated after correcting for perspective.

We estimate a lower limit of the discharge expansion velocity from frame 6 to be 5×10^5 m s^{-1}. The two first pulses are of short duration relative to the propagation time to maximum extent, which gives the visual impression of a pulse propagating upward with remaining emissions at higher altitudes. The last pulse of the discharge is of longer duration, fading more gradually and simultaneously over its entire vertical extent. From the pixel values and the approximate response of the camera, the brightness of the jet is estimated to be in the range of 0.2–0.4 MR [*Hunten et al.*, 1956]. The expansion velocity, color, and luminosity are consistent with blue jets reported in the past [*Schmetz et al.*, 2002; *Yair et al.*, 2013]; however, at this point we refrain from categorizing the event in past terminologies and stay with a pulsating "blue discharge." To our knowledge, these images are the first of pulsating discharges at the tops of storm clouds. They show the astonishing variety of forms that electrical activity can take as we continue to discover new varieties of discharges in and above thunderstorms.

We next present observations of kilometer-scale, blue discharges that appear to be occurring on the surface of the top layer of the cloud. During the 160 s of video footage, 245 such discharges were observed, corresponding to a rate of about 90 per minute. Examples are given in Figure 4, where the left column shows the discharges as observed and the right column presents the discharges superimposed on an image of the cloud for spatial orientation. The superimposition was corrected for camera movements by matching city lights present in the full frame. They appear at the very top of the cloud, but in different locations. Their spatial dimension is 4–9 km^2 and may last for more than one frame (42 ms), and they appear unrelated to lightning activity deeper in the cloud. We have ruled out the possibility that the discharges are scattered light from lightning flashes inside the cloud since all of these are observed to have a relatively weak blue component. The observation of blue surface discharges with these characteristics is, to our knowledge, the first of its kind. Although they may resemble pixies [*Lyons et al.*, 2003], their size is 1 order of magnitude larger and may last for longer; their longest duration is between 83 and 125 ms. The full movie of the events observed in the northern cloud together with an animation of the ISS position and GLD360 lightning data is given in Movie S1 in the supporting information.

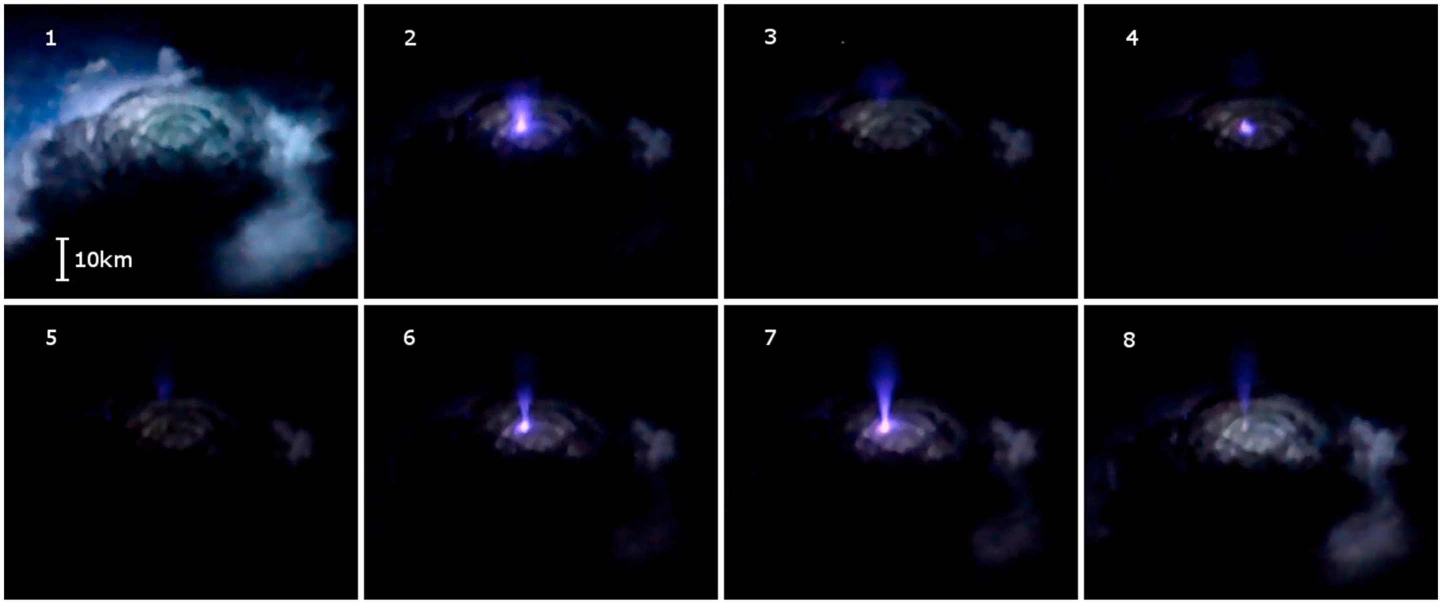

Figure 3. The pulsating blue jet from the top of the Northern cloud. Frame 1 is the first of the time sequence. It serves as a reference frame to illustrate the structure of the cloud. Frames 2–8 show the pulsating blue jet.

We now place the observations in the context of the thunderstorms that generate the events. For that purpose, we first estimate the cloud altitude from the Meteosat infrared cloud images that are a measure of the cloud top temperatures. We select three images at 1 h intervals that allow us to follow the three stages of the life cycle of the storm cell [e.g., *Yau and Rogers*, 1996, p. 223], from approximately 1 h before to 1 h after the overflight time of the ISS that occurred during the storm mature stage. To obtain the altitude from the temperature we use the temperature profile from the closest balloon sounding which was taken at 00:00 UT on 9 September from Chennai (Madras, 13.00°N, 80.18°E), which is ~200 km SW of the storm location and 1.5 h after the events studied. The derived altitudes are shown in Figure 5, and the sounding is included in Figure S1 in the supporting information together with wind speed and direction. We also considered soundings from Jagdalpur (19.08°N, 82.03°E, ~500 km NE) and Bhuaewar (20.25°N, 85.83°E, ~800 km NE), both close to the coast where the sea surface temperature has small variability [*Levitus*, 1982, p. 173]. The Chennai sounding shows a double tropopause at 15.8 and 18.2 km, while the soundings from the other stations show tropopause heights at about 16.5 km.

The atmospheric conditions were indeed very favorable for the development of deep convection. All three stations reported very humid conditions with nearly saturated air below 7 km and with convective available potential energy values between 1000 and 3000 J/kg. The equilibrium level is between 14 and 16 km, such that overshooting cumulonimbus turret may well have extended into the lower stratosphere. At all three stations, there is a considerable wind shear (most clearly visible in Chennai) with weak winds from the west below 6 km and strong winds from the east further above. Comparing with the altitude reconstruction presented on Figure 5, we see, on the middle frame, which is closest in time, the two active clouds reaching 15.8–18.2 km altitude, which is the altitude of the tropopause or even above according to the sounding data. We also see that the northern cloud, being indistinguishable from the larger cloud region an hour earlier, has developed rapidly, extending to the highest altitudes, probably with cloud turrets reaching into the stratosphere and that strong winds from the east further above displace the anvil cloud to the west of the updraft tower. The tops of the larger southern cloud complex, in contrast, appear to be sinking during the time shown, leaving a southern tall section still reaching the highest altitudes at the time of the overflight (middle frame).

The evolution of the thunderstorm is confirmed by data from the Machlipatnam Doppler weather radar. On Figure 1, the radar reflectivity at 22:21 UTC is shown on the top and right panels as function of altitude and geographic extent. The northern cloud with blue discharges is ~120 km from the radar, and the southern

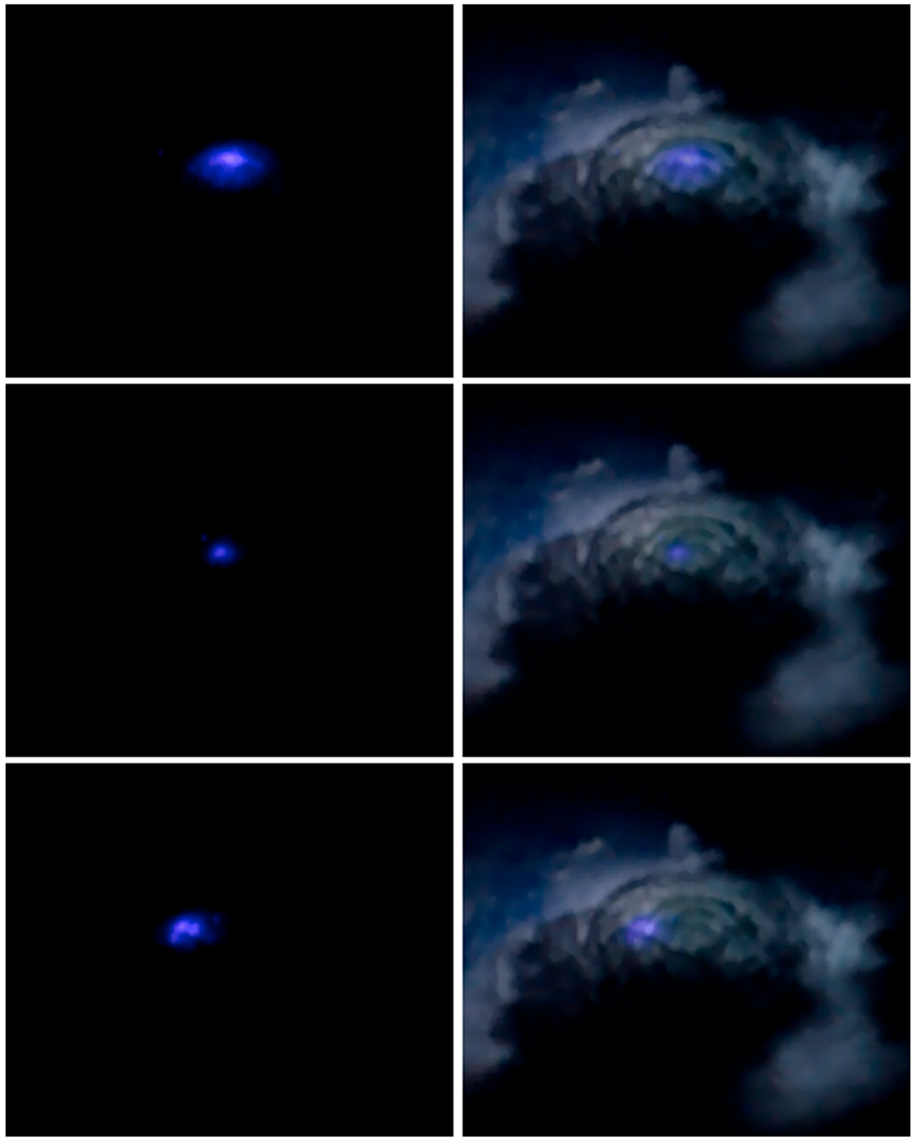

Figure 4. Blue surface discharges on the cloud top. (left column) The observed discharges; (right column) the discharges superimposed on an image of the cloud.

cloud is at the southern edge of the radar view. The location of the pulsating blue electrical discharge is within a few kilometers of a strong cloud core with a peak base radar reflectivity of about ~55 dBZ. The cloud altitude as function of longitude shows two peaks—one is for the northern cloud and one for the southern. We see that the northern cloud top is above 18 km at the time of observation, indicating that the top passed the tropopause, reaching into the lower stratosphere. The radar data show that the cell developed several kilometers in altitude during the preceding hour and collapsed during the following hour (see Figure S2). Both the cloud altitude and its evolution are consistent with the Meteosat observations.

We finally discuss the lightning activity as measured by the GLD360 global lightning detection network [*Said et al.*, 2013] that record both cloud-to-ground and intracloud activity, although not with discrimination. The data are presented in Figure S3, and the conclusions are given in the following. We considered data in two regions of $1° \times 1°$ in latitude and longitude, centered at the northern (15.5°N, 81.5°E) and southern (13.5°N, 81.5°E) cells. The negative lightning rate in the northern cloud increased from ~40 min^{-1} at 22:00 to ~120 min^{-1} at the time of the observation (22:21), suggesting a strong updraft [*Deierling and Petersen*, 2008], and then decayed to ~20 min^{-1} at 23:00. The rate in the southern part decayed from ~35 min^{-1} at

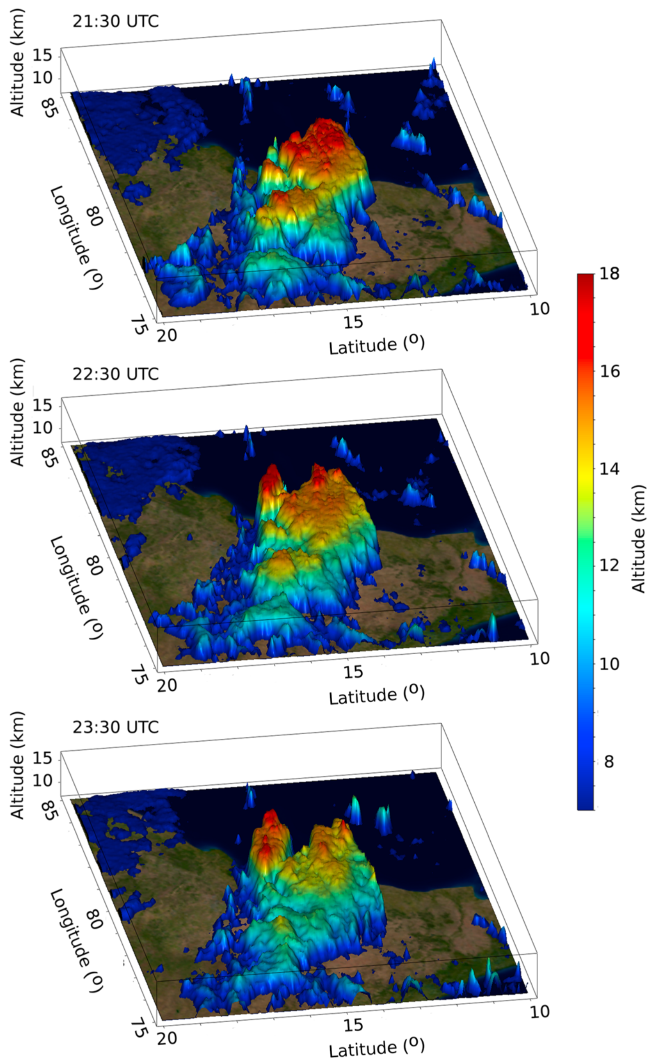

Figure 5. The cloud top altitude every hour from 21:30 UTC to 23:30 UTC. The altitude is reconstructed from Meteosat temperature and the closest sounding from Chennai (see details in the text).

22:00 to ~10 min^{-1} at 23:00, indicating a decaying thunderstorm. The evolution of the lightning activity is consistent with the Meteosat and radar observations, showing the three stages of the northern cloud. In comparison, the rate of blue discharge increased from 60 to 180 min^{-1} (1 to 3 s^{-1}) before the blue jet and decrease to an average of 120 min^{-1} (2 s^{-1}) after. A strong negative cloud-to-ground lightning at −167.5 kA occurred 1.16 s prior to the pulsating blue jet and may be related to it. Looking now at the time distribution and time differences between the blue discharges and global lightning dataset (GLD360) recorded lightning, no clear correlation is observed. The smaller discharges have an average time difference to the earliest preceding lightning events of 1.2 s with a standard deviation of about 1 s, whatever the polarity of the preceding lightning, and appear unrelated to lightning detected by the GLD360 sensors. We note that the rate of negative discharges exceeds the positive ones in the northern cloud, suggesting that the thunderstorm is of normal polarity [*Rust et al.*, 2005] and that the blue jet is most probably of positive polarity, discharging from a positive charge layer upward through a negative screening layer [*Riousset et al.*, 2010].

4. Discussion

The northern cell, where the blue discharges were observed, developed quickly (1 h) and expanded into the lower stratosphere. A strong updraft generates opposite polarity charge layers and high levels of lightning activity, consistent with the high rate of optical emissions observed from this cloud. In addition, the analysis of the GLD360 lightning data suggests that the cell has a normal charge structure. The most common, but oversimplified, configuration of thundercloud charge structure is with a negative charge layer at the center and positive charge layers above and below [*Stolzenburg and Marshall*, 2008]. In this simple view, blue jets are thought to be positive leader discharges in normal polarity storms, generated by the electric field between the top positive charge center and the negative screening layer formed by negative ions attracted from the atmosphere and ionosphere above [*Pasko et al.*, 1996; *Pasko*, 2008]. Once formed, the streamers continue past the screening layer and shoot up into the stratosphere, ionizing this region [*Krehbiel et al.*, 2008; *Riousset et al.*, 2010]. The observed velocity of our pulsating jet is above ~10^5 s^{-1}, which is faster than the minimum velocity observed for positive streamers [*Briels et al.*, 2007]. The conclusions on the storm polarity and the blue discharge velocities are therefore consistent with this view. However, the ISS images do not allow us to infer the depth from which the discharge originated. The fact that the discharge is pulsating adds to the complexity and variety of these events but does not necessarily change our overall understanding of their physics.

The small blue surface discharges appear to "dance" on the top of the cloud turret at a surprisingly high rate of about 120 per minute. The fact they are generated at the screening layer altitude is perhaps not surprising, as the threshold electric field at 18 km is only ~10% of its value at sea level. They may be related to turbulence in the cloud top layer and to the 1–100 m microdischarges created by instabilities in the convective flow of the cloud [*Trakhtengerts and Iudin*, 2005; *Bruning and MacGorman*, 2013]. However, the observed scale size of a few kilometer is larger than that of the microdischarges.

The meteorological conditions of the northern cloud, with fast growth to high altitudes, wind shear, and strong high-altitude winds, favor mixing and may prevent the buildup of a strong screening layer at the top [*van der Velde et al.*, 2010 and *Lazarus et al.*, 2015]. A weak screening layer may favor corona-type discharges, observed as the multitude of kilometer-scale blue discharges. Such discharges perturb the concentrations of greenhouse gases [*Mishin and Milikh*, 2008], which adds to other mechanisms for troposphere-stratosphere interactions, such as the transport of water vapor to the stratosphere [*Frey et al.*, 2015], the production of nitrogen oxides, and the depletion of stratospheric ozone [e.g., *Pan et al.*, 2014]. In *Winkler and Notholt* [2015] they estimate the production of nitrous oxides to be 10^{12} cm^{-3} in the streamer part of a blue jet at 18 km. With this estimate, the production from a volume of 1 km^3, representative of the kilometer-scale blue discharges, leads to 1660 mole per discharge. For comparison, the production of nitrous oxide by cloud-to-ground lightning and intracloud lightning is thought to be smaller and in the range of 100–1000 mole per flash [e.g., *Price et al.*, 1997; *Rahman et al.*, 2007]. As the flash rate for the blue discharge is comparable to the lightning rate, our observations may explain the higher concentrations of the various oxides of nitrogen observed in the stratosphere around thunderstorms compared to the values given by models [*Park et al.*, 2004]. From the convective available potential energy of 962 J/kg from the Chennai sounding station, the vertical velocity at the equilibrium level can be estimated to ~30 m/s [*MacGorman and Rust*, 1998]. The overshooting due to the strong updraft together with the substantial wind shear may have facilitated conditions for cloud top discharges. However, further observations are needed to clarify the more precise conditions required to assess their global impact on the atmosphere.

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References

Blanc, E., T. Farges, R. Roche, D. Brebion, T. Hua, A. Labarthe, and V. Melnikov (2004), Nadir observations of sprites from the International Space Station, *J. Geophys. Res.*, *109*, doi:10.1029/2003JA009972.

Briels, T. M. P., G. J. J. Winands, S. Nijdam, E. M. van Veldhuizen, and U. M. Ebert (2007), Exploring streamer variability in experiments, *J. Phys. D Appl. Phys.*, *41*, 234,004, doi:10.1002/2016GL071311.

Bruning, E. C., and D. R. MacGorman (2013), Theory and observations of controls on lightning flash size spectra, *J. Atmos. Sci.*, *70*(12), 4012–4029.

Chen, J. L., R. R. Hsu, H. T. Su, S. B. Mende, H. Fukunishi, Y. Takahashi, and L. C. Lee (2003), Global survey of upper atmospheric transient luminous events on the ROCSAT-2 satellite, *J. Atmos. Sol. Terr. Phys.*, *65*(5), 647–659.

Cicerone, R. J., J. D. Shetter, and C. C. Delwiche (1983), Seasonal variation of methane flux from a California rice paddy, *J. Geophys. Res.*, *88*(C15), 11,022–11,024, doi:10.1029/JC088iC15p11022.

Deierling, W., and W. A. Petersen (2008), Total lightning activity as an indicator of updraft characteristics, *J. Geophys. Res.*, *113*, doi:10.1029/2007JD009598.

Ebert, U., C. Montijn, T. M. P. Briels, W. Hundsdorfer, B. Meulenbroek, A. Rocco, and E. M. Van Veldhuizen (2006), The multiscale nature of streamers, *Plasma Sources Sci. Technol.*, *15*, S118–S129.

Ebert, U., S. Nijdam, C. Li, A. Luque, T. Briels, and E. van Veldhuizen (2010), Review of recent results on streamer discharges and discussion of their relevance for sprites and lightning, *J. Geophys. Res.*, *115*, doi:10.1029/2009JA014867.

Franz, R. C., R. J. Nemzek, and J. R. Winckler (1990), Television image of a large upward electrical discharge above a thunderstorm system, *Science*, *249*, 48–51.

Frey, W., R. Schofield, P. Hoor, D. Kunkel, F. Ravegnani, A. Ulanovsky, and T. P. Lane (2015), The impact of overshooting deep convection on local transport and mixing in the tropical upper troposphere/lower stratosphere (UTLS), *Atmos. Chem. Phys.*, *15*, 6467–6486.

Hunten, D. M., F. E. Roach, and J. W. Chamberlain (1956), A photometric unit for the airglow and aurora, *J. Atmos. terr. Phys.*, *8*(6), 345–346.

Jehl, A., T. Farges, and E. Blanc (2013), Color pictures of sprites from non-dedicated observation on board the International Space Station, *J. Geophys. Res. space phys.*, *118*(1), 454–461, doi:10.1029/2012JA018144.

Krehbiel, P. R., J. A. Riousset, V. P. Pasko, R. J. Thomas, W. Rison, M. A. Stanley, and H. E. Edens (2008), Upward electrical discharges from thunderstorms, *Nat. Geosci.*, *1*(4), 233–237.

Kuo, C. L., H. T. Su, and R. R. Hsu (2015), The blue luminous events observed by ISUAL payload on board FORMOSAT-2 satellite, *J. Geophys. Res. space phys.*, *120*(11), 9795–9804, doi:10.1002/2015JA021386.

Lazarus, S. M., M. E. Splitt, J. Brownlee, N. Spiva, and N. Liu (2015), A thermodynamic, kinematic and microphysical analysis of a jet and gigantic jet-producing Florida thunderstorm, *J. Geophys. Res. Atmos.*, *120*, 8469–8490, doi:10.1002/2015JD023383.

Levitus, S. (1982), Climatological atlas of the world ocean, in *NOAA Prof. Pap., 13*, p. 173, US Government Printing Office, Washington DC.

Lyons, W. A. (2006), The meteorology of transient luminous events—An introduction and overview, in *Sprites, Elves and Intense Lightning Discharges*, edited by M. Fullekrug, E. Mareev, and M. Rycroft, pp. 19–56, Springer, Netherlands.

Lyons, W. A., R. A. Armstrong, E. A. Bering, and E. R. Williams (2000), The hundred year hunt for the sprite, *Eos, Trans. Amer. Geophys. Union*, *81*(33), 373–377.

Lyons, W. A., T. E. Nelson, R. A. Armstrong, V. P. Pasko, and M. A. Stanley (2003), Upward electrical discharges from thunderstorm tops, *Bull. Am. Meteorol. Soc.*, *84*(4), 445–454.

MacGorman, D. R., and W. D. Rust (1998), *The electrical nature of storms*, Oxford University Press on Demand.

Mishin, E. V., and G. M. Milikh (2008), Blue jets: Upward lightning, *Space Sci. Rev.*, *137*, 473–488.

Neubert, T., M. Rycroft, T. Farges, E. Blanc, O. Chanrion, E. Arnone, and T. Bösinger (2008), Recent results from studies of electric discharges in the mesosphere, *Surv. Geophys.*, *29*, 71–137.

Pan, L. L., C. R. Homeyer, S. Honomichl, B. A. Ridley, M. Weisman, M. C. Barth, and J. H. Crawford (2014), Thunderstorms enhance tropospheric ozone by wrapping and shedding stratospheric air, *Geophys. Res. Lett.*, *41*, 7785–7790, doi:10.1002/2014GL061921.

Park, M., W. J. Randel, D. E. Kinnison, R. R. Garcia, and W. Choi (2004), Seasonal variation of methane, water vapor, and nitrogen oxides near the tropopause: Satellite observations and model simulations, *J. Geophys. Res.*, *109*, doi:10.1029/2003JD003706.

Pasko, V. P. (2008), Blue jets and gigantic jets: Transient luminous events between thunderstorm tops and the lower ionosphere, *Plasma Phys Contr. F.*, *50*, 124050.

Pasko, V. P., U. S. Inan, and T. F. Bell (1996), Blue jets produced by quasi-electrostatic pre-discharge thundercloud fields, *Geophys. Res. Lett.*, *23*(3), 301–304, doi:10.1029/96GL00149.

Pasko, V. P., U. S. Inan, and T. F. Bell (1998), Spatial structure of sprites, *Geophys. Res. Lett.*, *25*, 2123–2126, doi:10.1029/98GL01242.

Pasko, V. P., Y. Yair, and C. L. Kuo (2012), Lightning related transient luminous events at high altitude in the Earth's atmosphere: Phenomenology, mechanisms and effects, *Space Sci. Rev.*, *168*, 475–516.

Price, C., J. Penner, and M. Prather (1997), NOx from lightning: 1. Global distribution based on lightning physics, *J. Geophys. Res.*, *102*(D5), 5929–5941, doi:10.1029/96JD03504.

Rahman, M., M. Cooray, V. Rakov, V. A. Uman, M. A. Liyanage, P. Liyanage, B. A. DeCarlo, J. Jerauld, and R. C. Olsen (2007), Measurements of NOX produced by rocket triggered lightning, *Geophys. Res. Lett.*, *34*, doi:10.1029/2006GL027956.

Raizer, Y. P., and J. E. Allen (1997), *Gas Discharge Physics*, vol. 2, Springer, Berlin.

Riousset, J. A., V. P. Pasko, P. R. Krehbiel, W. Rison, and M. A. Stanley (2010), Modeling of thundercloud screening charges: Implications for blue and gigantic jets, *J. Geophys. Res.*, *115*, doi:10.1029/2009JA014286.

Rust, W. D., D. R. MacGorman, E. C. Bruning, S. A. Weiss, P. R. Krehbiel, R. J. Thomas, W. Rison, T. Hamlin, and J. Harlin (2005), Inverted-polarity electrical structures in thunderstorms in the Severe Thunderstorm Electrification and Precipitation Study (STEPS), *Atmos. Res.*, *76*, 247–271.

Said, R. K., M. B. Cohen, and U. S. Inan (2013), Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations, *J. Geophys. Res. Atmos.*, *118*, 6905–6915, doi:10.1002/jgrd.50508.

Sato, M., T. Ushio, T. Morimoto, M. Kikuchi, H. Kikuchi, T. Adachi, and I. Linscott (2015), Overview and early results of the Global Lightning and Sprite Measurements mission, *J. Geophys. Res. atmos.*, *120*, 3822–3851, doi:10.1002/2014JD022428.

Schmetz, J., P. Pili, S. Tjemkes, and D. Just (2002), An introduction to Meteosat second generation (MSG), *Bull. Am. Meteorol. Soc.*, *83*(7), 977–992.

Siingh, D., R. P. Singh, A. K. Singh, S. Kumar, M. N. Kulkarni, and A. K. Singh (2012), Discharges in the stratosphere and mesosphere, *Space sci. rev.*, *169*, 73–121.

Stenbaek-Nielsen, H. C., T. Kanmae, M. G. McHarg, and R. Haaland (2013), High-speed observations of sprite streamers, *Surv. Geophys.*, *34*(6), 769–795.

Stolzenburg, M., and T. C. Marshall (2008), Charge structure and dynamics in thunderstorms, *Space Sci. Rev.*, *137*, 355–372.

Trakhtengerts, V. Y., and D. I. Iudin (2005), Current problems of electrodynamics of a thunderstorm cloud, *Radiophys. Quant. El.*, *48*, 720–730.

van der Velde, O., J. Bór, J. Li, S. A. Cummer, E. Arnone, F. Zanotti, M. Fullekrug, C. Haldoupis, S. NaitAmor, and T. Farges (2010), Multi instrumental observations of a positive gigantic jet produced by a winter thunderstorm in Europe, *J. Geophys. Res.*, *115*, doi:10.1029/2010JD014442.

Vaughan, O. H., and B. Vonnegut (1989), Recent observations of lightning discharges from the top of a thundercloud into the clear air above, *J. Geophys. Res.*, *94*(D11), 13,179–13,182, doi:10.1029/JD094iD11p13179.

Wescott, E. M., D. D. Sentman, M. J. Heavner, D. L. Hampton, D. L. Osborne, and O. H. Vaughan (1996), Blue starters: Brief upward discharges from an intense Arkansas thunderstorm, *Geophys. Res. Lett.*, *23*(16), 2153–2156, doi:10.1029/96GL01969.

Winkler, H., and J. Notholt (2015), A model study of the plasma chemistry of stratospheric Blue Jets, *J. Atmos. Sol. Terr. Phys.*, *122*, 75–85.

Yair, Y., P. Israelevich, A. D. Devir, M. Moalem, C. Price, J. H. Joseph, and A. Teller (2004), New observations of sprites from the space shuttle, *J. Geophys. Res.*, *109*, doi:10.1029/2003JD004497.

Yair, Y., L. Rubanenko, K. Mezuman, G. Elhalel, M. Pariente, M. Glickman-Pariente, and T. Inoue (2013), New color images of transient luminous events from dedicated observations on the International Space Station, *J. Atmos. Sol. Terr. Phys.*, *102*, 140–147.

Yau, M. K., and R. R. Rogers (1996), *A Short Course in Cloud Physics*, Elsevier.