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Space shuttle observation of an unusual transient atmospheric emission

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[1] We report an observation of an unusual transient luminous event (TLE) detected in the near IR, south of Madagascar above the Indian Ocean. The event was imaged from the space shuttle Columbia during the MEIDEX sprite campaign [*Yair et al.*, 2004]. It was delayed 0.23 seconds from a preceding visual lightning flash which was horizontally displaced >1000 km from the event. The calculated brightness in the 860 (±50) nm filter was ~310 ± 30 kR, and the morphology of the emitting volume did not resemble any known class of TLE (i.e., sprites, ELVES or halos). This TIGER event (Transient Ionospheric Glow Emission in Red) may constitute a new class of TLE, not necessarily induced by a near-by thunderstorm. We discuss possible generation mechanisms, including the conjugate sprite hypothesis caused by lightning at the magnetic mirror point, lightning-induced electron precipitation and an extraterrestrial source, meteoric or cometary. **Citation:** Yair, Y., et al. (2005), Space shuttle observation of an unusual transient atmospheric emission, *Geophys. Res. Lett.*, *32*, L02801, doi:10.1029/2004GL021551.

1. Introduction

[2] All known forms of Transient Luminous Events (TLE) appear in conjunction with thunderstorm activity, especially those weather systems that generate intense positive cloud-to-ground flashes. The sequence of events is that ELVES appear first, generated by the interaction of the cloud-to-ground (CG) lightning induced electromagnetic pulse (EMP) with the lower ionosphere. Lasting 1 ms or less, they sometimes precede the appearance of sprite halos, which are a result of the quasi-electrostatic field (QE) of that same CG. If the conditions are appropriate - namely, positive CG polarity and sufficient charge-moment - a sprite will appear shortly after the halo, lasting tens of milliseconds. The time delay and lateral displacement of TLEs from their parent CG have been studied and modeled intensively. *Hu et al.* [2001] showed that ~33% of sprites are delayed more than 30 ms from the associated CG. *São-Sabbas et al.* [2003] report a mean time difference (Δt) of 30 ms between the parent +CG and the appearance of the sprite, with two extreme cases of 140 and 197 ms delay. The mean displacement (Δs) for the events studied was 40 km, with the respective Δs for the extreme cases being 51 and 75 km.

[3] The MEIDEX sprite campaign was conducted from the space shuttle Columbia in January 2003, and included 24 separate nocturnal viewing windows of the Earth's limb from an orbital altitude of 280 km. Details of the observation methodology are described by *Yair et al.* [2003]. In all, 17 TLEs were detected over Africa, South America, Australia and the Indian and Pacific Oceans. Most events could be easily classified [*Israelevich et al.*, 2004; *Yair et al.*, 2004].

[4] Here we report the detection of an unusual transient emission with a peculiar morphology. Shuttle-related sources for this event had been ruled out based on the mission operations time-line. The shuttle glow phenomenon [*Murad*, 1998] was also ruled out based on the physical detachment of the emission from the surfaces of the orbiter and its very short duration.

2. Optical Observations

[5] The observation was conducted by astronaut Ilan Ramon with the MEIDEX filter #6, centered at 860 nm (±40 nm). The space shuttle was entering the southern Indian Ocean after crossing the evening terminator into the night side over south-eastern Africa, and located at 33.32°S 45.18°E south of Madagascar. The camera was pointed exactly opposite to the shuttle's flown trajectory, to azimuth 284.9°. The gimbal data shows that the astronaut tilted it by 5 (±0.1)° north, to 290°. An active thunderstorm was observed near the limb with ~30 flashes occurring within the first 36 seconds of this observation window. The IR satellite image indicates the presence of convective clouds in Zimbabwe and Mozambique and over Madagascar with a cloud front extending over the ocean south of the MEIDEX FOV (Figure 1).

[6] In the video (Figure 2) Earth occupies the lower part of the image with a narrow band of atmosphere clear above the limb. The sunset light is seen as a bright region on the upper left side of the image. At 18:03:08.07 UT a lightning flash was observed, near the limb ~1800 km from the shuttle lasting 4 consecutive frames (132 ms). After the decay of the optical emission, there were 7 frames with no detection of any transient event (a delay >0.23 s). At 18:03:08.40 UT we detected a brief, unusual emission of light (Figure 3) superposed over the dark Earth. The emission had a distinct central bright part and a diffuse larger region, and lasted for only 1 frame (33 ms or less). The total (volume) brightness was found to be 310 kR. The location of the event can be estimated from the shuttle

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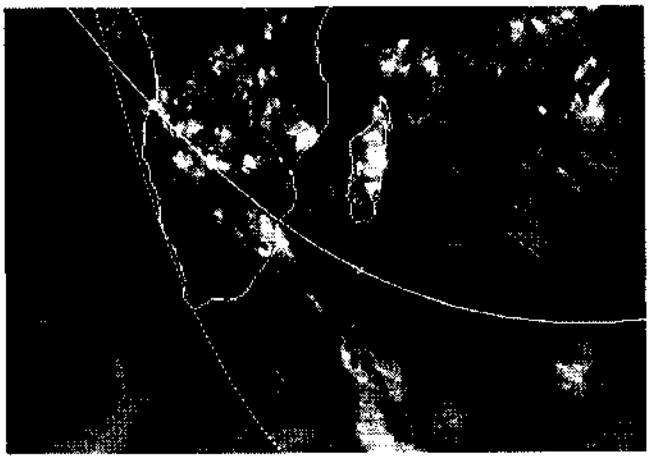

Figure 1. Space shuttle location and viewing geometry during orbit 66 (January 20th, 2003, 18:03:08.40 UT), superimposed on the IR satellite image from 18:00 UT. The shuttle track is marked by straight line, and the camera footprint on the surface is denoted by a dotted line. The terminator is west of the observed region and marked by a thick dotted line.

viewing geometry and the position of the emission within the image, although we need to constrain the altitude of the event in order to get an approximate ground footprint. We calculated the location for three assumed heights: 50, 100 and 150 km (Table 1). Obviously, the closer the event is to the space shuttle, the higher it must be in the atmosphere. Thus, the lateral displacement of this TLE from the preceding observed lightning seen in Figure 2 was found to be between 1280 and 1440 km.

3. Data From Ground Systems

[7] During the shuttle mission ground measurements of VLF and ELF signals associated with strong lightning discharges were conducted from a station in the Negev desert of Israel. ELF data was collected by 3 other stations located in Onagawa (Japan), Syowa (Antarctica) and Nagycenk (Hungary) [*Price et al.*, 2004]. Additionally, we used data from the experimental World Wide Lightning Location (WWLL) network being developed by Low Frequency Electromagnetic Research Ltd. [e.g., *Rodger et al.*, 2004], to locate major thunderstorm centers. The ELF data from our station showed that there were no prominent ELF transients in a time window ±2 seconds around the emission detection time. The Tohoku university group used a similar geolocation method for the Japan and Antarctica data [*Sato et al.*, 2003] and found no ELF transients either. The data from our VLF system and from the VLF WWLL network did not register any lightning event at the exact time of the emission; however it did pick up signals from the thunderstorms in that region (Figure 4). Thus, we are unable to correlate the event to any specific CG lightning near Madagascar.

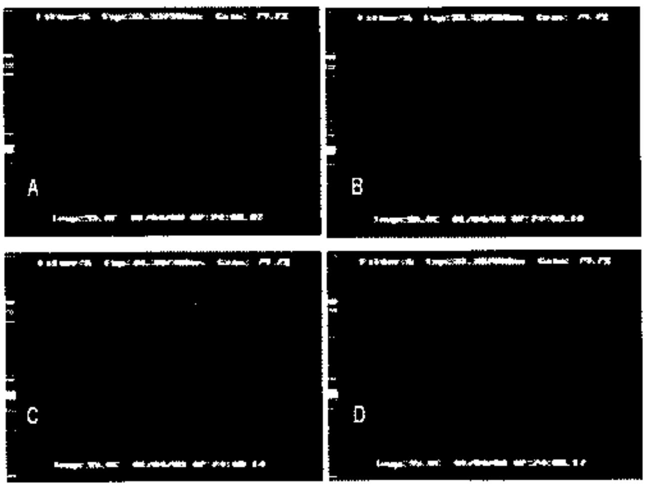

Figure 2. A lightning flash near the limb, seen in 4 consecutive frames (132 ms) observed from the shuttle in orbit 66 (January 20th, 2003, 18:03:08.40 UT).

4. Discussion

[8] The new observation reported here presents a unique deviation from the prevalent attributes of CG lightning-TLE relations and may possibly be a new type of TLE. We shall refer to it as TIGER (Transient Ionospheric Glow Emission in Red) for it bears little morphological resemblance to the known forms of sprites, haloes or ELVES, and is also very different from the typical luminosity pattern of cloud-diffused lightning light, which often has an elliptical shape and lasts several tens of ms. The temporal and lateral displacement of the event exceeds all those that were reported thus far, and excludes a relation to the visible flash seen near the limb. Thus even if we consider that our event is indeed a delayed sprite, the significantly larger temporal ($\Delta t > 0.23$ seconds) and lateral ($\Delta s > 1200$ km) dimensions are extremely unusual. Assuming that the event is a result of electron impact excitation processes like those operating in sprites or aurora, the emissions in the N-IR filter can be attributed to the N_2 first positive group (1PG) [*Bucsela et al.*, 2003]. However it is possible that other processes are in place and the glow is of a broadband source.

[9] Since the camera FOV draws an oblique rectangular pyramid from the space shuttle at 280 km toward the limb

Figure 3. The brief luminosity of the TLE as observed above the Indian Ocean, east of the main storm system. Based on the assumption that the event occurred at an altitude of ~100 km, the computed range from the shuttle is ~520 km, more than 700 km from near-by thunderstorms.

Table 1. Geographic Coordinates, Range From Shuttle, and Magnetic Conjugate Point for Three Possible Heights of the Emission

Emission Height	Range From Space Shuttle	Ground Footprint Coordinate	Magnetic Conjugate Point (T89c model)
50 km	700 km	(29.39°S, 39.66°E)	(43.77°N, 32.49°E)
100 km	520 km	(30.99°S, 40.05°E)	(44.96°N, 32.09°E)
150 km	360 km	(31.79°S, 41.76°E)	(45.49°N, 33.27°E)

1900 km away [see *Yair et al.*, 2004, Figure 1], one may argue that there could have been a lightning below the camera FOV which would have been missed in the image, and still be the parent for the observed TLE. Even if this was the case, the lateral displacement of lightning occurring outside the image from the event would have to be >500 km, a distance that still exceeds all reported displacements to date. Furthermore, the satellite IR image (Figure 1) shows that the area below the shuttle is almost clear of clouds making the possibility of a lightning less likely there. An ELVES forming below or to the south of the shuttle (where lightning were detected; see Figure 4) would expand for up to 600 km along the bottom of the ionosphere. This would bring some of that light into the camera FOV. A large dI/dt would produce the ELVES but not the ELF/VLF sferic at great distances. However the event does not resemble the known shapes of ELVES, so this possibility seems unlikely.

[10] An extraterrestrial source for this emission is one possibility that should be considered. Meteor trails were observed by the MEIDEX camera during orbit 87 on January 22nd, 2003 over Africa [*Yair et al.*, 2004]. Although most meteors start ablating in the atmosphere at heights around 110–115 km, there are also other reports of unusually high altitude emission from meteors [*Fujiwara et al.*, 1998]. *Frank and Sigwarth* [1997] have reported the detection of trails of OH emissions (in 308.5 nm) at low altitudes (<3000 km) in images taken by the Low-Resolution Visible camera on board the Polar spacecraft. The optical signatures were characterized by a bright core, surrounded by a larger, dimmer region of luminosity. They attributed these trails to an influx of water from mini comets in the vicinity of Earth, penetrating the atmosphere at a global rate of 5–30 events/minute.

[11] The TIGER event has similar morphological attributes to those of the hypothetical ablation products of mini-comets. Since it appears in the MEIDEX image to be very different from the well-known continuous trail of a meteor or a comet, the only geometry that can explain the signature is a very shallow entry angle, almost directly parallel to the camera line-of-sight. In such a case, we would be seeing the tail cross-section of the trajectory. However, the duration of luminosity for a shallow entry angle would have to be much longer than what was observed (<34 ms), because of the relatively prolonged period of atmospheric heating. Thus, it seems hard to reconcile both the morphology and the duration of the emission with that of an incoming body.

[12] A possible mechanism that may generate a TLE from a remote lightning flash was proposed by *Lehtinen et al.* [2001] who predicted that relativistic electron beams emitted from thunderstorms could impact the upper atmosphere in the magnetic conjugate hemisphere having been guided by the geomagnetic field, creating a transient purple glow, similar to a sprite and having roughly equal intensities in red and blue. This theoretical prediction led to the Conjugate Sprite campaigns conducted in 2002–3 in Europe, South-Africa, Australia and Japan, thus far with no success [*Marshall and Inan*, 2003]. For this explanation to be considered a valid interpretation of our TLE there should be a strong active thunderstorm in the northern hemisphere, near the conjugate magnetic point. According to geomagnetic field maps (NSSDC T89c field model, http://nssdc.gsfc.nasa.gov/space/cgm/t89.html), the Indian Ocean south-west of Madagascar mirrors north-west Turkey and the south-western shore of the Black Sea. The 17:33 UT NOAA satellite IR image and NCEP re-analysis maps show a closed cyclone located near Cyprus, over the Eastern Mediterranean Sea. This system was accompanied by a thick stratified cloud layer extending toward northwest over western Turkey and the area surrounding the Black Sea,. Such a meteorological scenario resembles the stratiform region of continental Mesoscale Convective Systems, found to be conducive to the production of strong +CGs, that are often accompanied by sprites [*Boccippio et al.*, 1995].

[13] There were no lightning measurements in what we term "the source region", due to the absence of a local network in western Turkey. However, signals picked by the VLF WWLL network for that period of time clearly demonstrate the occurrence of lightning there, and in the area near Cyprus (Figure 4). The Israel Electrical Company's Lightning Positioning And Tracking System (LPATS) picked up 66 CGs between 17:53–18:14 UT, from the area near Cyprus. This system is limited to a range of ~300 km from coastal Israel. One negative CG with a return stroke peak current of −26 kA occurred at 18:03:10.0 UT, within the ±2 seconds accuracy of the shuttle time stamp on the unusual TLE image (18:03:08.4 ± 2 s). This CG was located at (33.99°, N 34.42°E), and according to the T89c

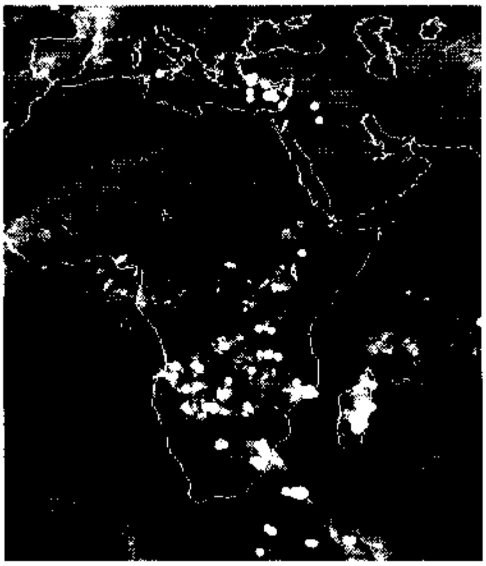

Figure 4. Lightning locations (white dots) derived from the VLF WWLL network for the time window 17:53–18:14 UT, showing the relative location in the eastern Mediterranean of the source region for the hypothetic electron beam that generated the observed TLE. Only "good" quality locations are included in the figure (<50 μs residual, 5 stations involved).

model its magnetic conjugate point at the surface is (17.57°S, 36.05°E). Considering the magnetic field line declination there (~34°) the correction for an event at 150 km height brings the predicted entry point of the postulated electron beam into the camera FOV, however with some offset to the location of the glow as deduced from the image. Lower altitudes result in larger offsets of the expected emission with respect to the actual location in the image.

[14] We would expect that the parent lightning of the conjugate sprite would be much more intense with a prominent signature in the ELF and VLF frequency domains. *Lehtinen et al.* [2001] calculate that for an electron beam to be energetic enough to have optical effects at the conjugate hemisphere, the +CG should remove 500 C from 15 km altitude. The −CG that was picked by the LPATS near Cyprus fails to meet this criterion, and seems unlikely to be the causative lightning for the observed glow. A larger CG should have (theoretically) been detected by the ELF and VLF stations that were operative during the MEIDEX, but this was not the case. Although non-detection does not negate the possibility of a +CG occurring within that time frame it is hard to explain the absence of any electromagnetic signal in all the stations.

[15] Another alternative explanation for the generation of the TIGER is by lightning induced electron precipitation (LEP). This mechanism is based on the loss of trapped radiation belt electrons due to resonant (lightning generated) whistler-mode wave-particle interactions. It was established by space-based measurements [e.g., *Voss et al.*, 1998] and theoretical models [e.g., *Clilverd et al.*, 2002] that lightning-produced whistlers can cause transient bursts of energetic electrons to precipitate and impact the ionospheric D layer. The travel-time from the lightning source along the magnetic line results in a shift in time and a poleward lateral displacement of the precipitating particles. The geometry of the storm seen in Figure 2 and the location of the N-IR emission to its south-east is in line with that of a LEP event. We looked in our Negev VLF data for the whistler signature of a flash with a sufficient delay to explain the TIGER, but failed to find such an event within the time frame. Additional VLF data is unavailable at this time to verify the LEP source.

[16] The here reported unique space-based observation stresses the need for monitoring the upper atmosphere by long duration orbiting platforms like the ISS and the ROCSAT-2 satellite with its ISUAL sensor [*Chern et al.*, 2003]. These and future missions will help elucidate similar unusual events.

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References

Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. T. Baker, and B. Boldi (1995), Sprites, ELF transients and positive ground strokes, *Science*, *269*, 1088–1091.

Bucsela, E., J. Morrill, M. Heavner, C. Siefring, S. Berg, D. Hampton, D. Moudry, E. Wescott, and D. Sentman (2003), $N_2(B^3\ \Pi_g)$ and $N_2^+(A^2\ \Pi_u)$ vibrational distributions observed in sprites, *J. Atmos. Sol. Terr. Phys.*, *65*, 583–590.

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

Clilverd, M. A., D. Nunn, S. J. Lev-Tov, U. S. Inan, R. L. Dowden, C. J. Rodger, and A. J. Smith (2002), Determining the size of lightning-induced electron precipitation patches, *J. Geophys. Res.*, *107*(A8), 1168, doi:10.1029/2001JA000301.

Frank, L. A., and J. B. Sigwarth (1997), Trails of OH emissions from small comets near Earth, *Geophys. Res. Lett.*, *24*, 2435–2438.

Fujiwara, Y., M. Ueda, Y. Shiba, M. Sugimoto, M. Kinoshita, and C. Shimoda (1998), Meteor luminosity at 160 km altitude from TV observations for bright Leonid meteors, *Geophys. Res. Lett.*, *25*, 285–288.

Hu, W., S. A. Cummer, W. Lyons, and T. E. Nelsom (2001), Lightning charge moment changes for the initiation of sprites, *Geophys. Res. Lett.*, *29*(8), 1279, doi:10.1029/2001GL014593.

Israelevich, P., Y. Yair, A. D. Devir, J. H. Joseph, Z. Levin, I. Mayo, M. Moalem, C. Price, and A. Sternlieb (2004), Transient airglow enhancement observed from the space shuttle Columbia during the MEIDEX sprite campaign, *Geophys. Res. Lett.*, *31*, L06124, doi:10.1029/2003GL019110.

Lehtinen, N. G., U. S. Inan, and T. F. Bell (2001), Effects of thunderstorm driven runaway electrons in the conjugate hemisphere: Purple sprites, ionization enhancements and gamma rays, *J. Geophys. Res.*, *106*, 28,841–28,848.

Marshall, R. A., and U. S. Inan (2003), Optical observations of conjugate sprites in South Africa, *Eos Trans. AGU*, *84*(46), Fall Meet. Suppl., Abstract AE42A-0794.

Murad, E. (1998), The shuttle glow phenomenon, *Annu. Rev. Phys. Chem.*, *49*, 73–98.

Price, C., et al. (2004), Ground-based Geo-location of TLE-producing intense lightning during the MEIDEX mission on board the Space Shuttle Columbia, *Geophys. Res. Lett.*, *31*, L20107, doi:10.1029/2004GL020711.

Rodger, C. J., J. B. Brundell, R. L. Dowden, and N. R. Thomson (2004), Location accuracy of long distance VLF lightning location network, *Ann. Geophys.*, *22*, 747–758.

São-Sabbas, F. T., D. S. Sentman, E. M. Wescott, O. Pinto Jr., O. Mendes Jr., and M. J. Taylor (2003), Statistical analysis of space-time relationship between sprites and lightning, *J. Atmos. Sol. Terr. Phys.*, *65*, 525–535.

Sato, M., H. Fukunishi, M. Kikuchi, H. Yamagishi, and W. A. Lyons (2003), Validation of sprite-inducing cloud-to-ground lightning based on ELF observations at Syowa station in Antarctica, *J. Atmos. Sol. Terr. Phys.*, *65*, 607–614.

Voss, H. D., M. Walt, W. L. Imhof, J. Mobilia, and U. S. Inan (1998), Satellite observations of lightning induced electron precipitation, *J. Geophys. Res.*, *103*, 11,725–11,744.

Yair, Y., C. Price, Z. Levin, J. Joseph, P. Israelevitch, A. Devir, M. Moalem, B. Ziv, and M. Asfur (2003), Sprite observations from the space shuttle during the Mediterranean Israeli Dust Experiment (MEIDEX), *J. Atmos. Sol. Terr. Phys.*, *65*, 635–642.

Yair, Y., P. Israelevich, A. D. Devir, M. Moalem, C. Price, J. H. Joseph, Z. Levin, B. Ziv, and A. Teller (2004), New observations of sprites from the space shuttle, *J. Geophys. Res.*, *109*, D15201, doi:10.1029/2003JD004497.

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