Observations of transient luminous events from space – a review

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Abstract

We review the results of space-based observations of Transient Luminous Events occurring in the mesosphere, occurring in conjunction with intense lightning flashes. The global rate of these events has significant implications on the global electrical circuit, combining the lower troposphere with the ionosphere. The needed TLE climatology can be best addressed by data from orbiting space platforms. The results from various such platforms are presented: from early space shuttle missions, the MEIDEX campaign, the LSO on-board the ISS and unmanned instruments on the ROCSAT-2 and RHESSI satellites. Future missions are briefly described.

Introduction

The well-known forms of mesospheric Transient Luminous Events (TLE) usually appear in conjunction with thunderstorm activity, especially those weather systems that generate intense positive cloud-to-ground flashes (Lyons et al., 2003). The different types of optical emissions have unique morphologies that reflect the physical processes taking place in the mesosphere, helping observers to distinguish between them. ELVES are large, circular and red in color, with a distinct hole in the middle that gives them the appearance of an expanding doughnut above the location of the parent CG. When viewed edge-on, they appear as narrow, extended, intense arcs of light with a horizontal dimension of several hundred kilometers. An oblique view would show ELVES as an elliptical ring of light with a distinct hole in the middle (Inan et al., 1997). Typical occurrence heights are ~85-105 km, coinciding with the emissions of the airglow layers (Fukunishi et al., 1996). Sprite haloes occur at altitudes from 70 to 85 km, and have a diffuse pancake-shaped appearance with no clear boundaries. They have a lateral dimension of tens of kilometers, lasting ~ 2 ms and usually precede the onset of streamer development typical of sprites (Miyasato et al., 2002). Sprites, the most structurally complex phenomenon (Gerken and Inan, 2003) emit in red and blue (Hampton et al., 1996) and span a vertical range between 50 and 90 km. They can take weird and magnificent shapes resembling jelly-fish, carrot heads, pearls or columns, and usually have distinct boundaries.

Sprites, haloes and ELVES seem to be ubiquitous around the planet, and were reported over most major centers of lightning activity on Earth. However, their global rate is still elusive and was not unequivocally determined. Thus, observations of the Earth from space offer an advantageous vantage point which allows the continuous monitoring and large scale coverage of these atmospheric phenomena. A space based observing platform of lightning-induced TLEs can overcome many limitations of ground-based measurements, especially the inherent locality of a site-based measurement and the line-of-site and cloud obscuration issues. Clodman (1999) described the advantages and difficulties of satellite detection of TLEs, and noted that certain wavelengths of TLE emissions can be best viewed from above, especially in the IR and UV parts of the spectrum.

The global rate of occurrence can be deduced and correlated with the meteorological characteristics of the parent storm, and with a proper choice of detector, these phenomena can be even viewed in daylight. Clodman (1999) also reviewed different alternatives for the viewing geometry and concluded that a pointable view by a satellite or from the space shuttle, directed at the earth's limb, may offer the most efficient way the detect TLEs from space. This methodology was suggested to best address the most severe limitation of space-based observations cited by Boeck et al. (1998), which was the inability to track a storm for a time span of minutes to hours. The following review describes the main efforts conducted thus far to observe TLEs from space and discusses some of the future directions in the coming decade.

Early Observations from the Space Shuttle

The first space-based images of TLEs were obtained from space shuttle video footage taken during the Mesoscale Lightning Experiment that was conducted in 1989-1991 (Boeck et al., 1992, 1995). Although the Low Light Level Video monochrome cameras of the space shuttles were not designed as scientific instruments and could not provide spectral information on sprite properties, it nevertheless served as a valuable tool in the initial research phase of the mid 90s (Boeck et al., 1998). The analysis of tens of hours of video yielded 17 events which were interpreted as sprites and jets (Figure 1). The limited time resolution of the shuttle video (0.017 s) resulted in the appearance of sprites in only a single video field, however the event sequence for the appearance of a sprite could still be determined. The oblique view from the shuttle of the illumination inside the cloud provided the first unambiguous optical link between the parent lightning discharge and the subsequent TLE. The wide geographical coverage of the shuttle orbit was a major factor in expanding the regions where TLEs were observed. Based on the shuttle trajectory and attitude and by using stars and ground lights, Boeck et al. (1995) deduced the approximate sprite locations and found that they occurred over Africa, South-America, USA, Australia, Borneo and the Pacific Ocean, always in conjunction with intense lightning activity. The first observation of ELVES can also be attributed to Boeck et al. (1992) who reported a sudden and short-lived brightening of the airglow layer above a thunderstorm near French Guyana. The limb view from the space shuttle showed a narrow layer of increased luminosity, with a large horizontal extent, which was calculated to be at an altitude ~95 km. This event was remarkably different from all the vertical and narrow flashes that were seen in other shuttle images, and was considered a new class of TLE. This new type was later confirmed by Fukunishi et al. (1996) and Inan et al. (1996), and named ELVES.

The MEIDEX sprite campaign

After the conclusion of the MLE in 1991, there was a twelve year hiatus of space shuttle observations of TLEs which lasted until the Mediterranean Israeli Dust Experiment (MEIDEX) campaign, conducted in 2003 on-board the ill-fated space shuttle Columbia [Yair et al., 2003]. The STS-107 mission lasted 16 days, with orbital inclination 39° at an altitude of 278 km. The MEIDEX payload consisted of two bore-sighted cameras, a Sekai wide-FOV color camera for target acquisition, and a Xybion IMC-201 multispectral radiometric science camera, equipped with a rotating filter wheel (5 Hz) equipped with 6 narrow-band filters. The central wavelengths were 340nm, 380nm, 470nm, 555nm, 665nm and 860nm, chosen specifically to enable correlative measurements of desert dust aerosols with the MODIS instrument on board NASA's Terra satellite and the TOMS sensor. Xybion cameras of other models were used for ground measurements of sprites by Lyons et al. [1995] and by other researchers. It was equipped with a 50mm UV lens, adjusted with a special baffle to mitigate stray light from entering the optics. The FOV was rectangular, 10.76º vertical and 14.04º horizontal (diagonal 17.86º), with a 486x704 pixels CCD, where each pixel corresponds to $1.365{\cdot}10^{-7}$ steradian. The video format was NTSC at 30Hz (33.3 msec/frame), recorded internally on 3 digital tapes and also in the shuttle crew-cabin for backup. The camera went trough several calibrations at NASA/GSFC Laboratory for Atmospheres, ensuring the absolute translation of gray levels to energy units. For a limb distance of 1900 km the camera field-of-view covered the altitude range 0-200km, where all TLEs occur. Both cameras were mounted on a single-axis gimbal, enabling a 22° scan to each side, expanding the total potential observation area on the limb to more than 1600 km. The geometry of observation had the shuttle flying either tail-to-earth or nose-to earth, with the camera line-of-site pointed at the horizon. The sprite campaign had to maximize observation opportunities by instructing the astronauts to visually observe lightning activity and to direct the gimbaled camera toward these regions. Contrary to remote-controlled or automatic robotic observations, the human factor played a significant and indispensable role in the real-time target acquisition, greatly enhancing the probability of capturing TLEs.

TLE observations during the MEIDEX-sprite campaign were performed in 24 dedicated observation windows, each approximately 20-minute long. In all, 583 minutes were recorded in the crew-cabin, of which 458 minutes were transmitted to the ground. The data that was transmitted to the ground from 21 orbits comprises a 358 minutes database. Clearly, not all observations were conducted over stormy regions, and only ~1/5 of the database had some lightning activity. The results were described by Israelevich et al. (2004), Yair et al., (2004, 2005) and Price et al., (2004). In total, 17 events were confirmed: 10 Elves and 7 sprites, with ~20 suspicious events that were not easily identifiable. The sprites were located between 40 and 90 km above ground, and the ELVES altitude was estimated to be ~95 km (Figure 2). The calculated sprite brightness was in the between 0.3-1.7 MR in the 665 nm filter (corresponding to the red emission from $N_2$1P) and between 1.4-1.7 MR in the 860 nm filter. Sprites were found to occur above oceanic and continental storms, and the calculated occurrence rate for the tropics was 12 events per minute. The MEIDEX data showed for the first time that ELVES are also produced by intra-cloud flashes, in which case the resulting shape of the TLE is an arc or a narrow band, without the signature "donut" hole in the middle (Figure 3).

In addition to the detection of known species of TLEs, Yair et al. (2005) reported a unique observation of what they termed "Transient Ionospheric Glow Emission in Red" (TIGER). The emission was detected with the 860 nm filter, south of Madagascar above the Indian Ocean, and was delayed 0.23 seconds from a preceding visual lightning flash which was horizontally displaced > 1000 km from it. The calculated brightness was ~310±30kR, and the morphology of the emitting volume did not resemble any known class of TLE (i.e. sprites, ELVES or halos). The TIGER event may constitute a new class of TLE, not necessarily induced by a near-by thunderstorm. Possibly, it was a LEP induced event or maybe a conjugate sprite.

Observations from the International Space Station

The International Space Station is orbiting the earth at an altitude of 350 km in an orbital inclination of 57°. The ability for a continuous observation of transient luminous events by the ISS crew was demonstrated during the LSO experiment, conducted be French and Belgian astronauts in 2001 and 2002 (Blanc et al., 2004). The observation geometry from inside the station was by looking directly down above the thunderstorm, in the nadir. This necessitated inventing a method for discrimination between the emission from the parent lighting and the ensuing TLE. The experimental setup was based on two calibrated, 512 x 512 pixels CCD micro-cameras, positioned inside the station and fixed to a window. The cameras had a FOV of 70° and took simultaneous images that were saved on a computer disk. In order to reduce the transmission time of the images to the disk, only the central half of the images was saved. The minimum exposure time was 1 s with a time resolution of 1 s, much longer than the typical duration of lightning and TLE.

The unique feature of the LSO was the use, in one of the cameras, of a very narrow spectral filter, centered at 761 nm, with a width of ±10 nm. This filter allowed the detection of intense emission from the Nitrogen first-positive line ($N_2$1P 3-1) found in sprites at 767.2 nm, and also of the oxygen line near 761.9 nm (which is hard to observe from the ground due to O_2 absorption). The system was operated automatically during the night part of the ISS orbit, above continents, where the probability to observe lightning activity is larger compared to the oceans (Christian et al., 2003). This was done by special software, without crew involvement in pointing or tracking. The LSO collected 3.5 hours of useful data, and detected 60 transient events, out of which 13 were detected in both cameras, hinting at the presence of sprite light in addition to the lightning (Figure 4). Blanc et al. (2004) confirmed 10 sprites for 280 lightning flashes, with radiances in the range of 10-100 MR. Such high values are a result of the nadir view, which essentially integrates all the emission along the sprite's larger dimension. The calculated power of the lightning events that were detected by both LSO cameras (and hence, were probably the sprite parents) was of the order $5x10^{11}$ to $4x10^{12}$ W in the visible, comparable to the power of intense superbolts reported by Turman (1978). The high luminosity value can be explained by the presence of large continuing currents in sprite-producing flashes, a fact established by many studies (Cummer, 2003; Sao-Sabbas et al., 2003). The system remains on-board the ISS but has lately malfunctioned and at present cannot be re-activated to collect additional data (E. Blanc, personal communication, 2005).

Satellite Observations of TLEs - ISUAL on board ROCSAT-2

The ISUAL (acronym for: Imager of Sprites and Upper Atmospheric Lightning) payload on-board the ROCSAT-2 satellite is a joint project of Taiwan, Japan and the US. Being the first dedicated satellite mission to study TLEs, it was launched successfully on May 21st 2004, into a polar, sun-synchronized orbit at an altitude of 891 km. The payload is described by Chern et al. (2003), and consists of a CCD imager, a 6-channel spectrophotometer and a 2-channel array photometer. The observations are triggered by a rapid increase in the input of the spectrophotometer, which operates in 6 parallel channels. The photo-multiplier tubes of the spectrophotometers are wide band in 180-310 nm, 608-753 nm and 228-410nm, and narrow band in 337 nm, 391.4 nm and 777.4 nm. The Array Photometer is designed to obtain altitude information of TLEs and has a FOV of 3.6°x22.6°. It is made of 2 boresighted photometers sensitive to the blue ($N_2$2P) and red ($N_2$1P) emissions, integrating over 16 horizontal channels with a sampling frequency of 2 or 20 kHz.. The ISUAL imager is using a filter wheel with 5 filters, centered on the main emission lines of sprites and the airglow. The observations are conducted in a limb-viewing geometry, with a 5° vertical and 20° horizontal FOV. The limb is 3190 km away and hence the lateral coverage of the ISUAL imager is 1219 km, with a vertical span of 223 km. The swath of the satellite does not allow the full coverage of the planet and leaves gaps that are always missed by the detector, even though this gap can be minimized by altering the detector's orientation. On-orbit instrumental calibration was performed, to ensure the accuracy of the timing and ground projection.

The preliminary results from the ROCSAT-2 satellite were reported by Mende et al., (2004), Su et al., (2004), Frey et al., (2004) and Fukunishi et al., (2004). Clearly, the satellite fulfilled its design goal and observed TLEs over all major thunderstorm areas on Earth, with a detection rate of 7.6 events per day. ELVES were observed by the imager in 2 forms (with and without the central hole), confirming the results reported by Israelevich et al. (2004) which were attributed to different types of parent flashes (cloud-to-ground vs. intracloud). Some ELVES were observed clear from the light of the preceding flash which was obscured behind the limb, a fact that enabled getting pure spectra and deduce the existence of ionization in ELVES. Most sprites were found to occur within 10 ms from the parent flash, however ~23% were delayed between 10-120 ms. Since it is planned for a 5-year mission duration, it is expected that the accumulated ISUAL data will form a planetary TLE climatology, that is needed in order to estimate the global impacts of these events.

Satellite Observations of Terrestrial Gamma Flashes - RHESSI

A new addition to the family of lightning related transient luminous events may be considered the discovery of terrestrial gamma flashes (TGFs), initially detected by the NASA Compton Gamma-Ray Observatory (Fishman, 1994). In over 9 years of data, 76 such events were found. With ~1 millisecond duration, these flashes were identified to originate from thunderstorms, and the postulated mechanism was the acceleration of high-energy electron beams from below, that generate energetic bremsstrahlung photons which eventually reach the space-based detector.

Lately, Smith et al (2005) reported the discovery of numerous TGFs in data obtained with the RHESSI satellite (acronym for Reuven Ramaty High Energy Solar Spectroscopic Imager). This NASA Small Explorer platform orbits the Earth in a 38° inclination orbit at an altitude of 600 km, and has a 2700 km line-of-sight to the horizon. The satellite's germanium detectors are capable of detecting photons arriving from all directions. In 8 months of data, they reported finding 125 TGFs, with a duration of 0.2 - 3.5 ms. Based on an estimate of ~1000 km footprint, they calculated a daily rate of ~50 events, however this may be a conservative estimate of the beam radius, and the true rate may be 2 orders of magnitude larger. Possibly, a larger number of events may exist below the satellite's detection threshold. The RHESSI data set already shows that the locations of most TGFs correspond to the major lightning centers over the tropical continents. Since the relationship between TGFs, sprites and ELVES is not fully understood yet, a considerable effort is being now directed at finding correlations between the ELF and VLF signatures of sprite-producing lightning and the occurrence of TGFs. The mission will keep enlarging the TGF database and eventually enable finding the relation between the parent lightning properties, TLE appearance and the generation of high-energy electron beams.

Future Missions

The clear advantages of space-based platforms in obtaining long-term global distributions and high-quality morphological and spectral data of TLEs, and the advances made in detector sensitivity and data storage capabilities, offer a powerful incentive for new, additional, platforms. Several such missions are in different conceptual planning stage:

- EQUARS - the Brazilian satellite dedicated to study lighting, airglow and TLEs.
- TARANAIS - A French micro-satellite designed to monitor lightning and sprite activity.
- Additional LSO campaigns from the ISS, and/or new payloads in the framework of the European and Japanese external platforms.

Undoubtedly, Earth-orbit offers the best vantage point to explore the upper reaches of the atmosphere, which still hold some elusive phenomena.

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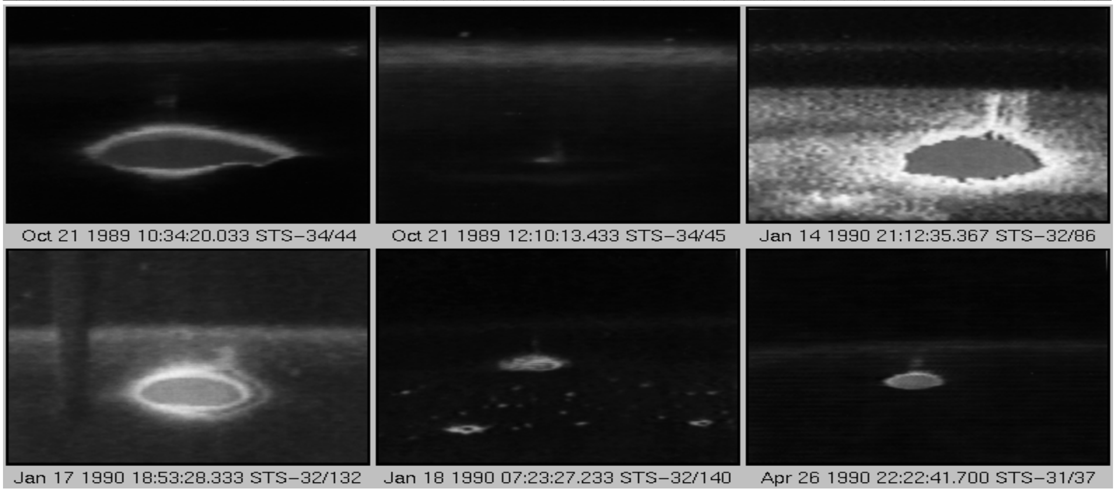

Figure 1: Images obtained during the MLE by shuttle payload bay low light-level TV cameras. The elliptical shapes are usually cumulonimbus anvils illuminated by the lightning flash. In some images, a vertical protrusion is apparent above the cloud, possibly a sprite. Image is courtesy of W. L. Boeck.

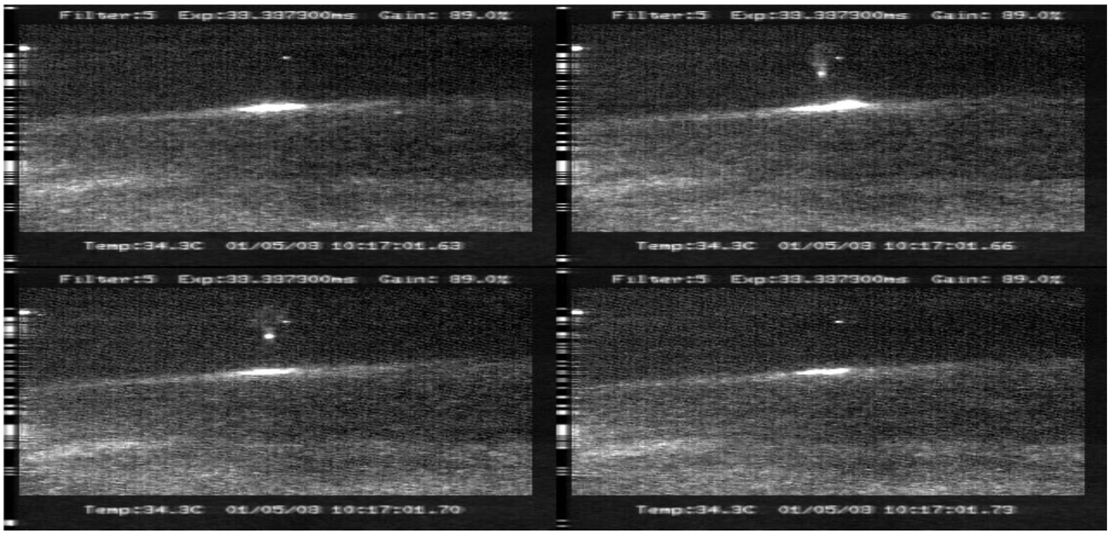

Figure 2: A sequence of images obtained by the MEIDEX payload, on January 22nd 2003 over central Africa. With superior temporal and spatial resolutions, the images show a carrot sprite above a nocturnal tropical thunderstorm.

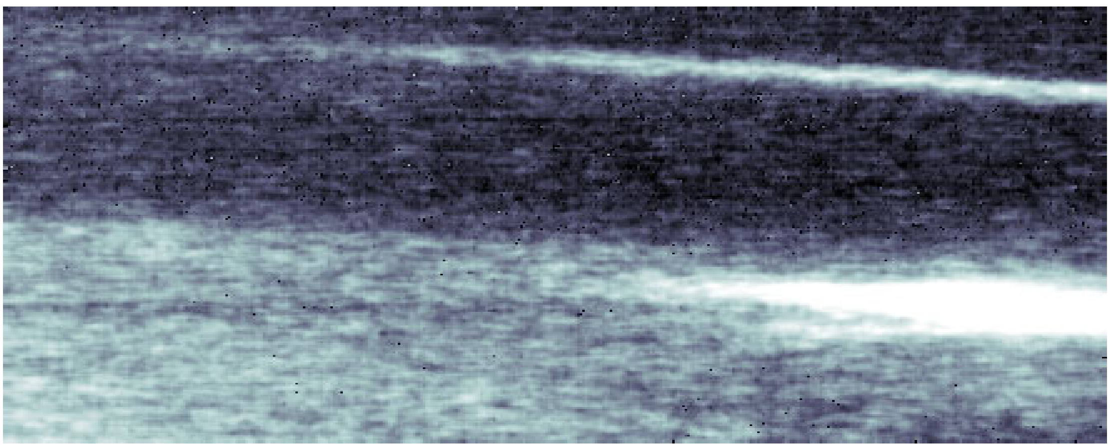

Figure 3: The slant, bright arc image of ELVES obtained by the MEIDEX payload. The bright region at the lower section is the cloud illumination by the causative flash. This is the first indication that ELVES can be produced by intracloud flashes.