Geophysica (2010), 46(1–2), 79–90

Observations of TLEs Above the Baltic Sea on Oct 9 2009

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(Received:May 2010; Accepted: October 2010)

Abstract

Two types of Transient Luminous Events (TLEs), an Elves and a sprite, were imaged at high latitudes (about 59.3°N 21.3°E) above a thunderstorm in northern Europe near Finland during the night of October 9th, 2009. The observations were made by Timo Kantola, a member of the Finnish Astronomical Association (Ursa), who has been maintaining a meteor-fireball camera in central Finland since 2006. Deduced from the photographs, the altitudes of the events were estimated to be 88 km (Elves) and 60 km (top of the sprite). The horizontal size of the Elves was estimated to be 269 km. The lightning location data of the Finnish Meteorological Institute (FMI) show several lightning locations during the night from which the parent strokes could be deduced. Also, waveform recordings of a pulsation magnetometer at Sodankylä Geophysical Observatory (SGO) show the located flashes. However, unfortunately the photographs are sum images over six minutes, which means that the exact times of individual frames, i.e., the exact TLE times, are not known accurately enough to allow exact attribution to a specific parent flash. These TLE observations are unique, because to the best of our knowledge, there are no previous reports of TLEs at such high latitudes in the northern hemisphere.

Key words: Transient luminous event (TLE), lightning location, Baltic Sea

1. Introduction

Transient Luminous Events (TLEs) are lightning-related phenoma occurring in the upper atmosphere between the cloud top and the ionosphere. TLEs are relatively new members in the field of thunderstorm research; the first detailed observations were made in 1989 in the U.S. by *Franz et al.* (1990), although the phenomenon itself had been suggested already in the early 20th century (*Wilson,* 1925). TLEs are related to thunderstorms but they are not similar discharges like the more frequently observed cloud-to-ground (CG) and intracloud (IC) lightning. Instead, TLEs are a consequence of a CG flash. Often, TLEs have been noted to accompany especially a flash of positive polarity (+CG) with high peak current (*Boccippio et al.*, 1995). The mechanism of TLE formation is nowadays known reasonably well, but especially the microphysical properties are still a bit of a mystery.

TLEs occur in various shapes, sizes and forms, according to which different types of TLEs have been named and classified. The best-known types are Elves, sprite, halo, blue jet, and gigantic jet (*Pasko et al*., 2002). All TLE-types have different occurrence mechanisms. The physical mechanisms of TLEs have been discussed in detail in several previous publications (see e.g. *Sentman et al.,* 1995, *Wescott et al.,* 1995, *Fukunishi et al.,* 1996, *Barrington-Leigh et al.,* 2001) and an overview of the specific types of optical emissions have been presented by *Pasko* (2007), so we will address them here only briefly. The formation of sprites is caused by the sudden and intensive change in the intensity of the electric field of the thunderstorm. Usually, TLE-producing storms have a large horizontal dimension which makes the charge distribution of the cloud top to resemble a plate charge;. in suitable conditions, the electric field of a thundercloud may extend to high altitudes (~100 km). The accepted mechanism for the generation of sprites is based on the rapid rearrangement of charge within the thunderstorm after a powerful positive cloud-to-ground flash. The removal of the positive charge leads to generation of a quasi-electrostatic (QE) field above cloud top, extending into the mesosphere for several miliseconds (*Pasko et al.*, 1997). This field affects and accelerates the free electrons which reside below the ionosphere; the accelerated electrons collide with the upper atmospheric air molecules (mainly nitrogen) and the molecules emit faint light by the changes in their states of excitation. Sprites are usually ignited around ~80 km and may extend down until 50 km, depending on the duration and strength of the continuing current in the parent flash (*Cummer et al.*, 2006)

Elves occur when a strong electromagnetic pulse (EMP) emitted by a CG influences the ionosphere. There is no polarity dependence like in the case of sprites, and so both positive and negative cloud-to ground flashes can trigger Elves. The optical intensities of TLEs are approximately 0.1–10 MR (megarayleigh; for a comparison, the optical intensity of the aurora is about 1 MR). The duration is typically a few milliseconds.

TLEs have been observed widely all around the world, and in principal, they should occur wherever there is lightning activity. *Chen et al.* (2008) show the global distribution of TLEs according to the observations of the ISUAL instrument (Imager of Sprites and Upper Atmospheric Lightning) onboard the FORMOSAT-2 satellite (*Chern et al.,* 2003). The instrument covers latitudes 45°S–45°N, i.e., the northernmost Europe is not within its coverage. Apparently, the northernmost TLE observations with ISUAL have been made in Europe in U.K. (Fig. 3 in *Chen et al.,* 2008). Basically, the highest number of TLE observations are found in areas which experience a high amount of thunderstorms per year, namely summer-time continents in the tropics and mid-latitudes. Also, because the emission of light from sprites and Elves is weak, ground-based observations are difficult or even impossible to make during the daytime. In the high latitudes, where the thunderstorm season has a strong correlation to the summer season, the observations are hampered by the almost constant existence of sunlight during night hours, because the sun is above the horizon. The best possibility to observe a TLE at high latitudes would be during a late-summer nocturnal thunderstorm; the storms may still be intense, and the evening and night hours are already dark enough.

This is what happened on October 9 2009 in Finland; an extensive late summer convective system approached Finland from the Baltic Sea during the nigh, exhibiting a substantial lightning activity.

In this paper we present details of the observations of the high-latitude TLEs made by Timo Kantola. The paper outlines are as follows. Section 2 describes briefly the thunderstorm climate of Finland. The case study of the TLE observations are described in Section 3. Section 4 presents some discussion.

2. Thunderstorms and observation methods in Finland

2.1 Thunderstorm climate of Finland

Finland is situtated in the northern part of Europe between latitudes 60–70°N. The thunderstorm season begins typically in May and ends in September (Fig. 1); thunderstorms also occur outside this period, but they are usually weak and produce only a few flashes. On average, about 140,000 ground flashes occur during the year, which equals to a ground flash density of 0.4 fl. km^{-2} yr^{-1}. The average (local) thunder day number is 12; during about 100 days per year thunderstorms occur somewhere in Finland (*Tuomi and Mäkelä,* 2008a).

The thunderstorm climatology of Finland contains a large variation both in the number of storms and flashes per year but also in the occurrence regions of the most violent storms. The location of Finland between two highly different climatological zones, the Atlantic maritime climate and the Asian continental climate, has an effect on the thunderstorm climate; according to *Tuomi and Mäkelä* (2003, 2008a). Even though most of the thunderstorms in Finland are related to the weather systems arriving from the western sector (Atlantic), the most favourable conditions for intense thunderstorms are related to the air masses approaching from the eastern sector, i.e., from the southern and eastern Europe.

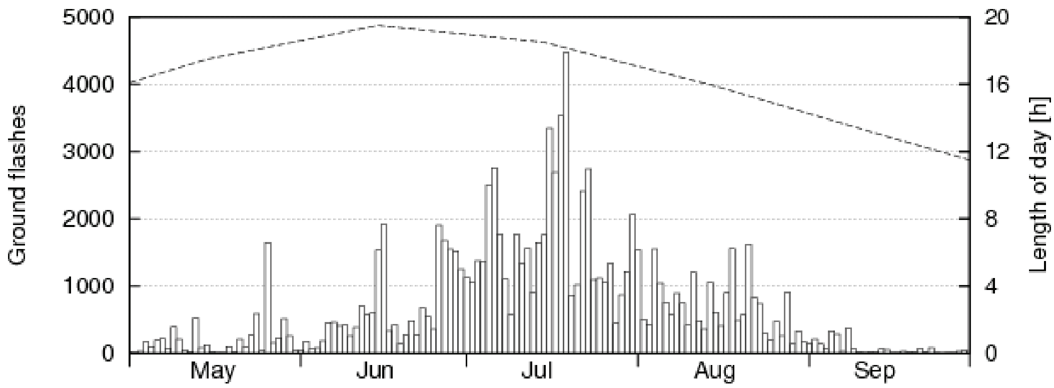

Fig. 1. The average daily number of CGs in Finland in 1998-2009 (boxes) and the day length (dashed line, hours) in the southern Finland.

2.2 Observation methods of TLEs

Although the Finnish Meteorological Institute (FMI) maintains the national lightning location system (LLS), and participates and contributes to the international scientific research about thunderstorms, FMI does not have equipment for monitoring TLEs. The research resources are mainly channeled to provide better warning tools of convective hazards for practical purposes. However, FMI has been using voluntary work related to the observations of meteorological phenomena (*Tuovinen et al.*, 2009, *Rauhala and Schultz,* 2009), and especially the Finnish Astronomical Association (Ursa) has been cooperating with FMI for years; FMI provides to the Ursa volunteers and storm spotters real time information about severe weather situations, and as a feedback, the volunteers report from the field how the situation looks *in situ*. This approach is extremely fruitful for both parties.

Ursa maintains also several automatic cameras for observing the night sky. The cameras are not specially designed to observe TLEs, but fortunately, similar cameras are widely used all around the world for TLE imaging adapted with automatic software to record only frames containing a transient event (*Yair et al.*, 2009). The position of the Kantolas camera is 62.258°N 27.109°E and it is shown in Fig. 4. The camera technical details are:

- Watec watt902H 1/3" b/w (sensitivity 0.0005 Lux F1.4)
- optics Computar 2.7-8 mm f1.0 (TG3Z2710FCS), focal length is set 2.8 mm
- software used for the photos is Skypatrol4ccd

One frame is composed of two collated fields; while the other field is being exposed the camera electronics is reading the other field. The frame rate is 25 frames per second, which makes 50 fields per second. The software uses every second field which makes 25 fields per second. The sum image is so called peakhold -image: during the 6 minute exposure the first field assigns a value for each pixel between 0–255 according to the sum (brightness + thermal noise + reading noise) of the received signal. Then, the values from the next field are compared to the previous one, and if the sum is larger, this value is stored, etc. During the 6-minute window each pixel is checked about 9000 times to find out the brightest value. Furthermore, individual frames are stored if the object meets certain conditions; unfortunately, in the case presented here no individual frames were stored, which means that exact occurrence times of the TLEs are not available, only the 6 minute time-windows.

The data is checked routinely on almost day-to-day basis, but longer gaps may occur. For example, in the case presented in this manuscript the camera had been running a few days without checking the data. No automatic feature in the analysis software was available to pinpoint the TLEs from the data, which means that the camera user found the events by browsing through the image archive from the past couple of days. It is clear, that without the sharp eye for all peculiar objects in the data, these observations would have never been found. The camera has been running around the clock for about four years, which comprises nearly 6 billion video fields in which two of them contained the TLEs; also in this sense, we can fairly say that the observations are unique, serendipitious and rare.

2.3 Lightning location system

The present FMI LLS has been in operation since 1998. The LLS locates mainly CG strokes, but also to some degree of intracloud (IC) lightning. The LLS consists of so called IMPACT-type low frequency (LF) sensors and their successors manufactured by Vaisala Inc. (see e.g. *Cummins et al.,* 1998, *Cummins and Murphy*, 2009). Besides the temporal and spatial information of strokes, the system estimates also the peak current of each located stroke. Also, three VHF (very high frequency) sensors of so called SAFIR-type (*Richard et al.*, 1986) have been in operation since 2001 for total lightning detection in southern Finland. Since 2002, FMI has been cooperating with the neighbouring countries Norway and Sweden, and later in 2005 with Estonia, to combine their sensors into a common network called NORDLIS (Nordic Lightning Information System). The coverage area of the network is practically the whole Scandinavia (Fig. 2), and the detection efficiency is estimated to be about 90-95 % (*Tuomi and Mäkelä,* 2008b, *Mäkelä et al.,* 2010), depending on the region. Location accuracy is approximately 500 m at the central and western parts of Finland, and 1.0 km at north and east (*Mäkelä et al.,* 2010).

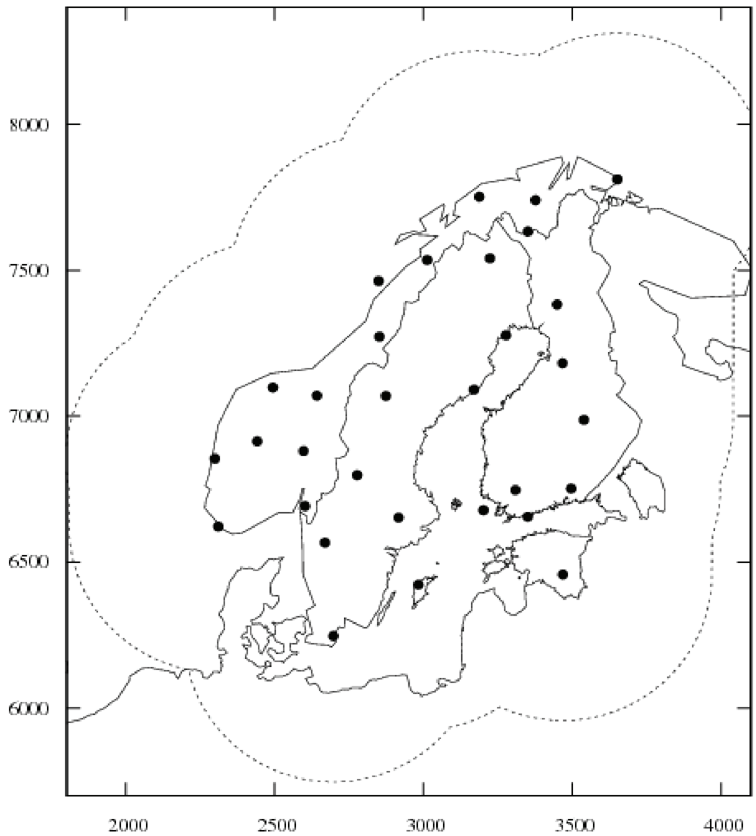

Fig. 2. NORDLIS lightning location system. Black circles are sensor locations, and the dashed line indicates the coverage area. X- and y-axis values are kilometres to the East and North, respectively.

2.4 SGO's pulsation magnetometer chain

Sodankylä Geophysical Observatory (SGO) operates Finnish pulsation magnetometer network, which covers latitudes from 60°N (Nurmijärvi) to 69°N (Kilpisjärvi) in Finland (*Lukkari et al.,* 1977). This network aims to monitor fast variations of the Earth's magnetic field and particle processes in the magnetosphere. Present instrumentation of the network samples the signal at 40Hz, resulting in poor resolution for the observed TLE events. However, prototype of the new pulsation magnetometer was in test use with 200Hz sampling with GPS timing in Sodankylä. Two orthogonal search coils stores lightning generated EMPs propagating in the magnetic field. Digital waveform of the signals of North-South oriented coil is presented in Figure 4.

3. Case study of Oct 9 2009

Fig. 3 shows the satellite image at 00:02 UTC (03:02 local time) and weather radar image at 00:40 UTC on Oct 9 2009. A frontal weather system was located over the Baltic sea during the night, propagating to the northeast. Embedded heavy precipitation was present, which suggests convective activity. Indeed, a total of 75 CGs were detected during the night (Fig. 4). Regarding the number of located flashes, the storm cannot be classified as intense, but as can be seen from Fig. 4, the lightning-producing area was extensive. The conditions were suitable for a typical late summer thunderstorm; cool and dry air mass over the warm sea surface triggered deep moist convection.

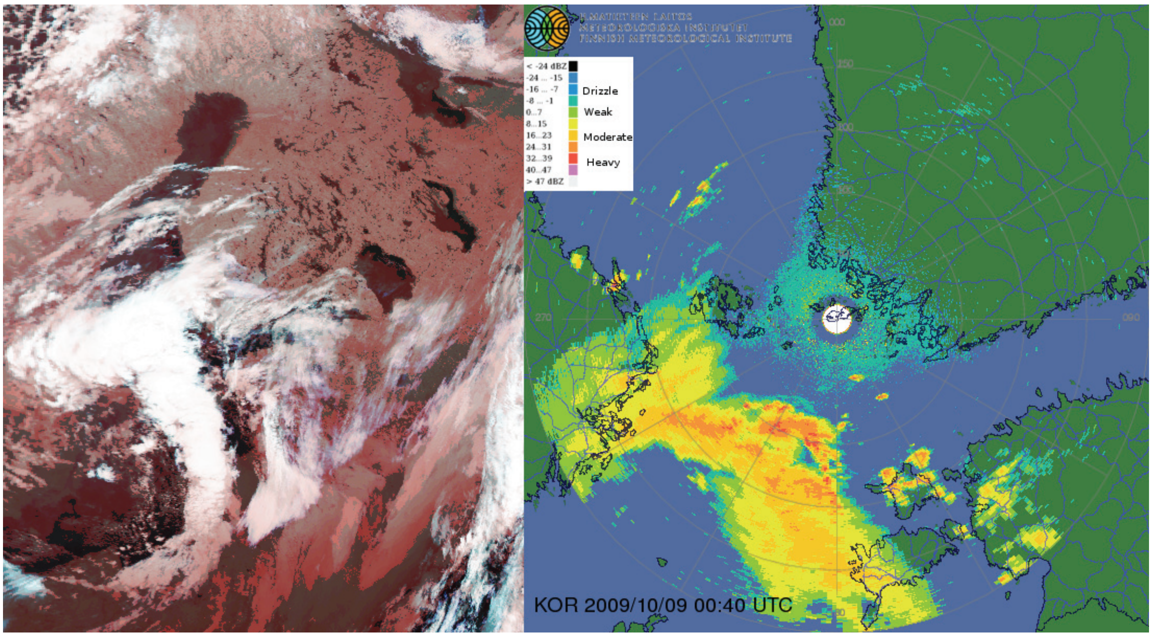

Fig. 3. Satellite image (left) at 00:02 UTC (03:02 local time), and weather radar CAPPI-image (right) at 00:40 UTC from Oct 9 2009.

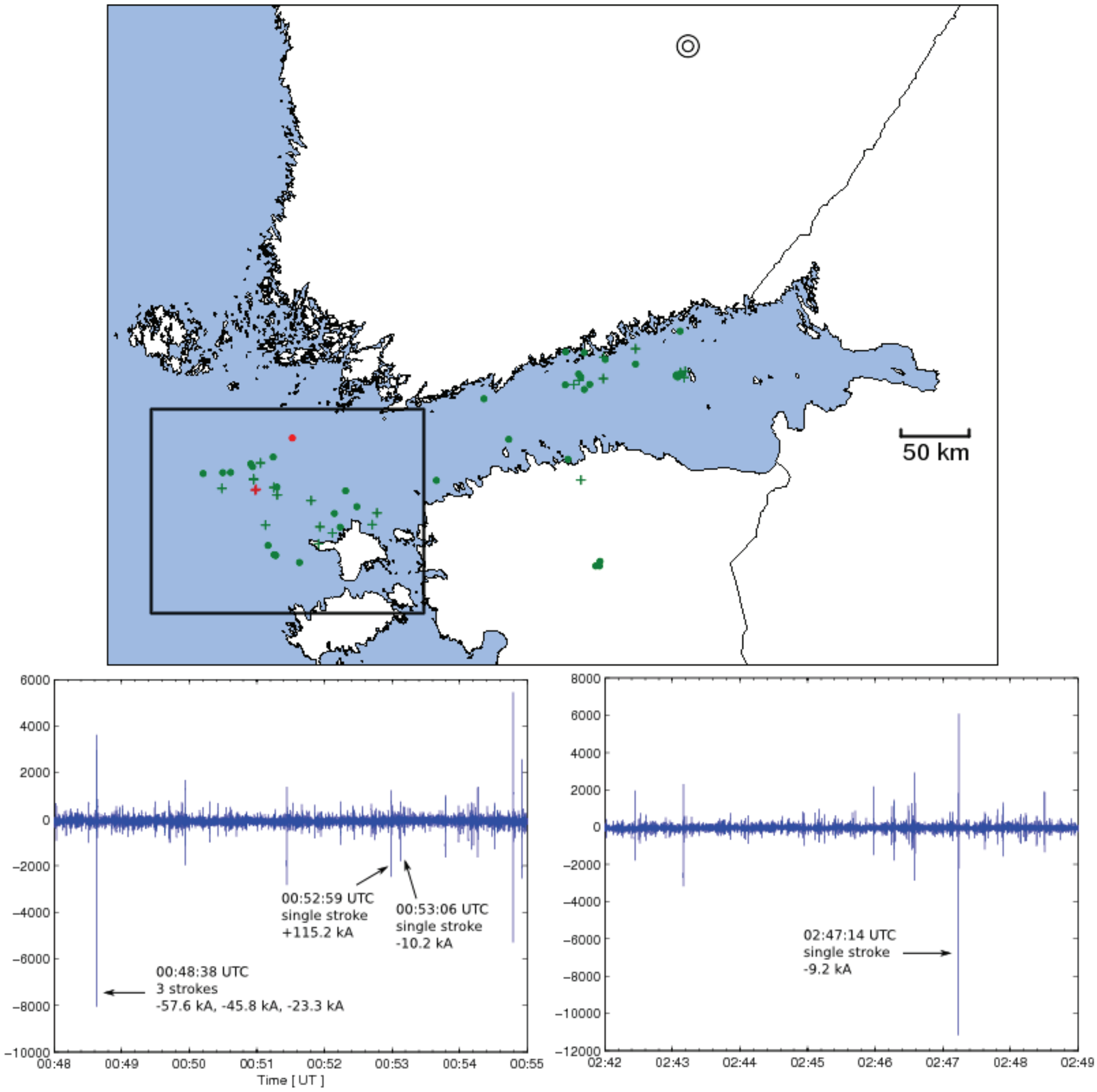

Fig. 4. Upper: CG locations from Oct 9 2009. Plus-signs and filled circles indicate positive and negative CGs, respectively. Red coloured locations are the suspected parent flashes of the TLEs. The double circles indicate the camera position. Below: Pulsation magnetometer observations recorded at Sodankylä (67.42°N, 26.39°E), approximately 950 km from the thunderstorm. Some of the located flashes are visible in the waveforms.

The time window for the first TLE observation (Elves) was at 00:48:09 – 00:54:10 UTC (Fig. 5). During that time, a total of 6 CG flashes (9 strokes) were located over the Baltic Sea. Two of the flashes were of positive polarity, the other having extremely high estimated peak current (115.2 kiloamperes, kA). The occurrence time of this flash was at 00:52:59.3423 UTC. The location of this intensive flash is at the correct azimuth (227.20° ± 0.05°, elevation 8.60° ± 0.10° from the camera site) of the center of the Elves deduced from the photograph of Fig. 5. However, as discussed before, the exact parent-flash cannot be determined with 100% certainty because of the lack of exact time of the TLE. The distance to the lightning location is about 500 km from the camera. Based on the distance and elevation information, the calculated altitude of the event is 88 km.

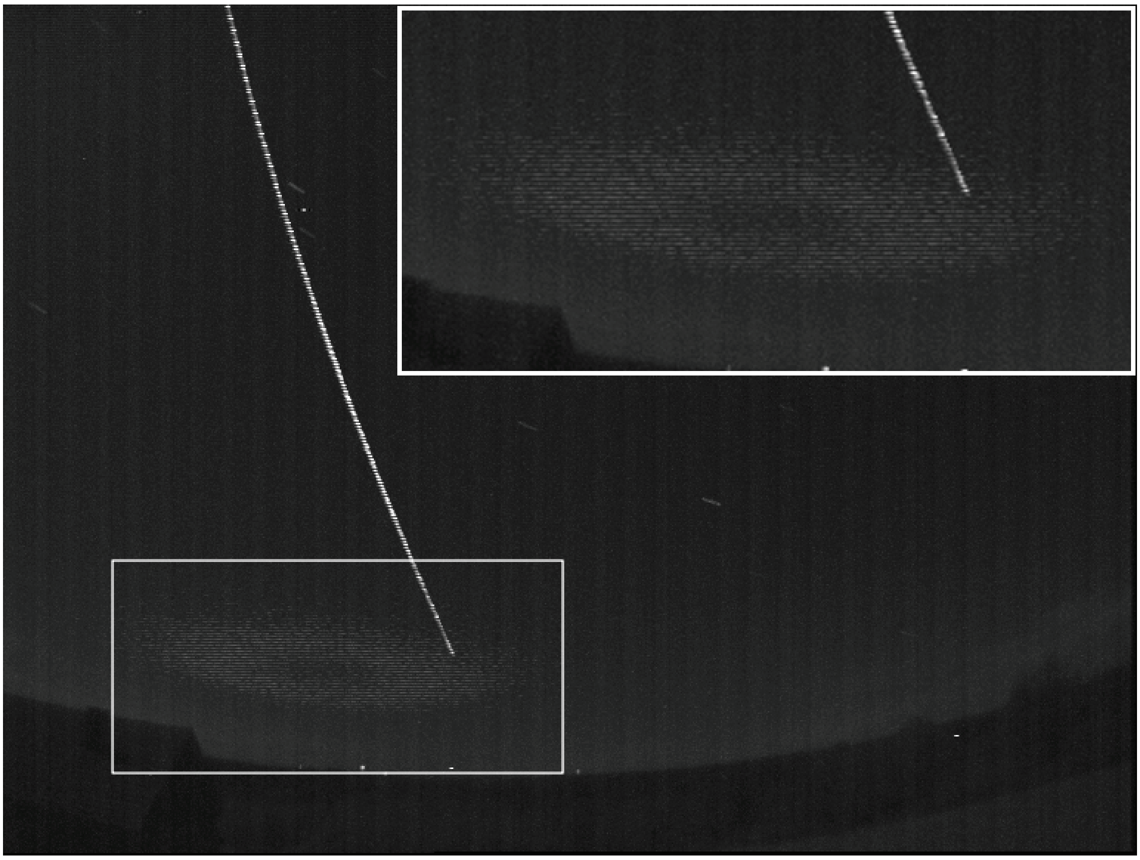

Fig. 5. Elves observed from Pieksämäki between 00:48:09 – 00:54:10 UTC. Note the “doughnut” shape with the hole in the middle. The diagonal streak is due to an airplane. The altitude of the event is 88 km.

A few hours later, at 02:42:58 – 02:48:59 UTC, another TLE (sprite) was observed (Fig. 6). According to the photograph, the position is not much different from the Elves (azimuth 229.70° ± 0.05°, elevation of the sprite top 6.75° ± 0.10°). Only one lightning location fits this time window; a negative single-stroke flash with estimated peak current -9.2 kA at 02:47:14.0767 UTC. We strongly suspect this to be the parent flash because no other lightning locations are in the vicinity. The altitude of the top of the sprite is 60 km, based on the elevation and distance information. This altitude is comparatively low to observations of TLE's in midlatitides, where the average height is above 85 km (*Pasko et al*., 1997).

To back up and to resolve the ambiguity of the lightning location data, waveform recordings of a pulsation magnetometer from Sodankylä Geophysical Observatory were checked (Fig. 4). For the time window of the first TLE (Fig. 4 lower left), several peaks are visible in the waveform, which coincide with the located CGs. The suspected strong positive 115.2 kA flash is also visible in the waveform. However, the ambiguity still remains for this TLE. For the second TLE (Fig. 4 lower right) only one peak is visible in the waveform, which also coincides with the located -9.2 kA flash; therefore it seems very likely that this is the parent flash. Also, VHF lightning location observations (not shown) indicate a total of 58 located discharges at the time of the -9.2 kA flash, and no other VHF locations were made in this area inside the 6-minute time window. This furthermore suggest that the -9.2 kA flash is the parent flash. However, since present research shows that 98% of sprites are related to strong positive cloud-to-ground flashes (see review by *Neubert et al.*, 2008), the present observation of a negative parent lightning with a rather low peak current is puzzling and makes this case extremely unique. However, there are examples that sprites can be produced by negative flashes (*Barrington-Leigh et al.,* 1999) and also by intracloud flashes (*Van der Velde et al.*, 2006). It is also possible, that there may have been a positive cloud-to-ground flash during the 6 minutes which was missed by the system, but this seems unlikely because two individual lightning location systems have not detected other flashes. We have also consulted operators of ELF/VLF (*Greenberg et al.*, 2009) lightning location systems in Hungary and Israel, but these did not detect any lightning signal coming from the region of the Baltic Sea.

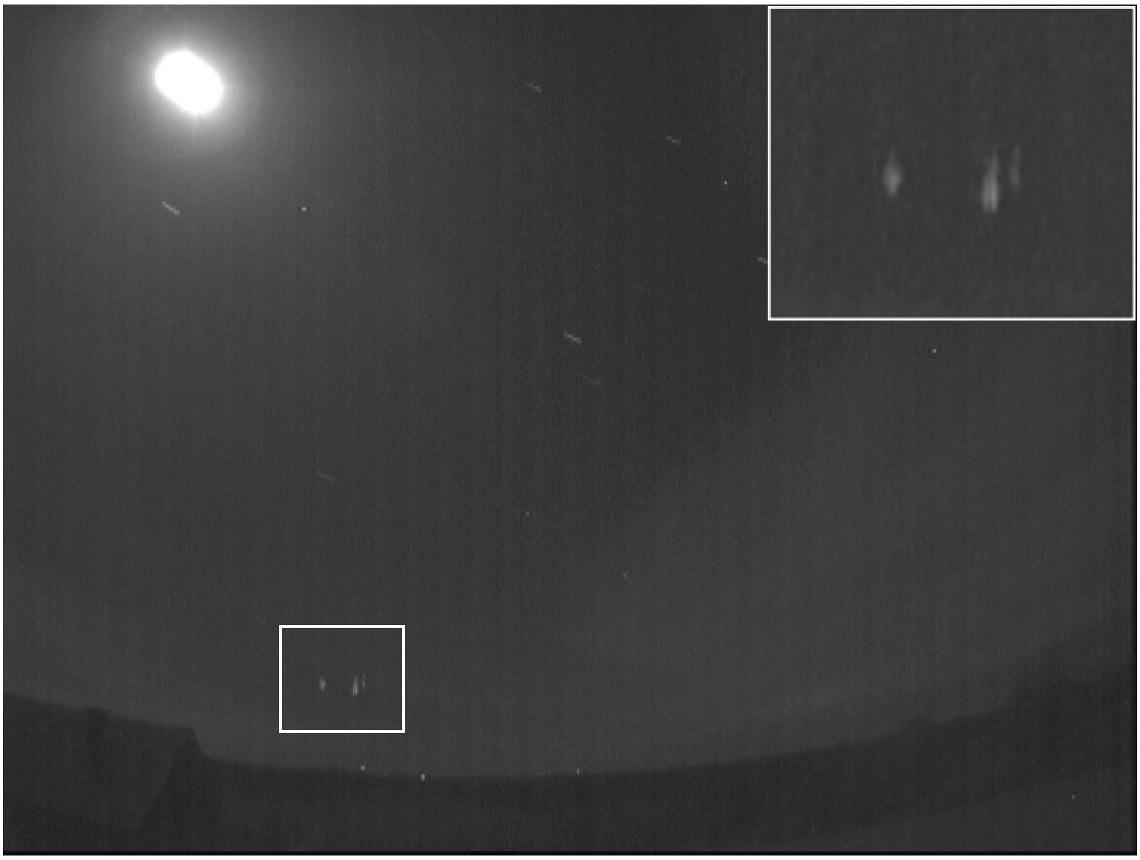

Fig. 6. Sprite observed from Pieksämäki between 02:42:58 – 02:48:59 UTC. This type is called “column” sprite, where separate elements may be displaced by several km from each other. The altitude of the top of the middle sprite is 60 km.

4. Summary and conclusion

We have presented observations of Transient Luminous Events (TLEs), an Elves and a sprite, at high-latitudes (about 59.7°N). To the best of our knowledge, no prior observations exist at such high latitudes in the northern hemisphere. The observations were made by a semi-professional sky-camera maintainer Timo Kantola, who has observed the night sky for several years in the central part of Finland.

One interesting issue regarding our observations is the suspected parent flash of the sprite; the negative polarity and small peak current (-9.2 kA) make this observation rare but also peculiar on a global scale.

To observe TLEs at high latitudes is challenging because (i) the thunderstorm season (summer) is highly sunlit, and (ii) intense thunderstorms during the dark season are relatively rare. However, otherwise there should not be any reasons why TLEs could not occur also at high latitudes. Indeed, the photographs shown in this article provide the first proof of high-latitude TLE-activity. Also, the storm spotter section of the Finnish Astronomical Association (Ursa) are designing a field campaign for the coming summers to get more observations of these upper-atmospheric phenomena. Because these campaigns are aimed specifically for TLEs, more detailed information (e.g., the exact occurrece time) will be very likely obtained.

Acknowledgements

We thank the Ursa people (Esko Lyytinen, Veijo Mäkelä, Marko Pekkola, Timo Roschier) and FMI personel (Dr. Tapio J. Tuomi, Panu Lahtinen) for the discussions and support on the analysis of the data in this paper. We thank Prof. Martin Fullekrug, Dr. Jozsef Bor and Dr. Gabriela Satori for providing their experts view about these TLE observations. We thank Antti Kero and Carl-Fredrik Enell for their help regarding the pulsation magnetometer data. We are grateful for Dr. Tapio J. Tuomi and Dr. Jakke Mäkelä for their encouragement to write this paper.

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