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Optically perceptible characteristics of sprites observed in Central Europe in 2007-2009

Abstract

Sprites are luminous optical emissions accompanying electric discharges in the mesosphere. 489 sprite events have been observed with a TV frame rate video system in Central Europe from Sopron (47.68 °N, 16.58 °E, ~230m MSL), Hungary between 2007 and 2009. Characteristic sprite forms, i.e. column, wishbone, tree, angel, and carrot have been identified in the set of records. Characteristic morphological properties corresponding to each type are given; earlier definitions and observations as well as the related theoretical considerations are reviewed. Based on the knowledge and experience from high-speed imaging in sprite observations, probable time sequences of streamer propagation directions were associated with the characteristic sprite types. It is suggested that different streamer propagation sequences corresponding to different dynamic processes may result in similar sprite forms. Several occasionally detectable sprite features are noted and described: tendrils, glows, puffs, beads, and spots. Spots are distinguished from the similar beads by their characteristic brightness, size, and location relative to the bright body of the sprite. The events observed in Central Europe have been classified by the number of individual sprites and by the variety of types appearing in them. More than 90% of the recorded sprites were found to occur in clusters rather than alone, and more than half of the sprite clusters contained more than one sprite types. Jellyfish and dancing sprite events are described as being special subsets of sprite clusters. Statistical analysis of the occurrences of morphological types, various sprite features, and event durations indicated that jellyfish sprites and clusters of column sprites with glows and tendrils do not tend to have long optical lifetimes. Sprite events with more morphological types, on the other hand, more likely have extended durations. The maximum of the encountered event duration was lower for events with many sprite elements. Observed rates of glows and puffs may refer to the occupied height range of sprites. The importance of understanding the driving factors behind the development of various sprite types and sprite features is emphasized and some topics are suggested for further investigation.

Keywords: sprite; morphology; cardinality; optical duration

1. Introduction

Sprites are one type of Transient Luminous Events (TLEs) (Lyons et al., 2003; Neubert et al., 2008; Pasko et al., 2012) appearing in the upper atmosphere above thunderstorms in the altitude range of ~40 to ~90 km. These brief luminous optical emissions have been observed from space (Boeck et al., 1995; Yair et al., 2004; Chen et al., 2008; Kuo et al., 2011), from airplanes (Sentman et al., 1995), from balloons (Bering et al., 2004) and from the ground in different parts of the world: in North and South America (Franz et al., 1990; Wescott et al., 1998b; Thomas et al. 2007; São Sabbas et al., 2010), in Africa (Williams et al., 2010), in Australia (Hardman et al., 2000), above the Sea of Japan (Myokei et al., 2009), in Taiwan (Su et al., 2002a), in China (Jing et al., 2008), and in the Europe (Neubert et al., 2008; Bór et al., 2009; Iwański et al., 2009; Ondrášková et al., 2010; Mäkelä et al., 2010) including the eastern Mediterranean region (Ganot et al., 2007; Yair et al., 2009). Telescopic imaging revealed that these emissions have a fine structure of streamers (Gerken et al., 2000), and high-speed camera records showed the development of complex forms in detail (Stanley et al., 1999; Moudry et al., 2003, McHarg et al., 2007; Stenbaek Nielsen and McHarg, 2008; Li and Cummer, 2009; Montanyà et al., 2010; Stenbaek-Nielsen et al., 2010). The observations showed that there is a rich variety of sprite forms and that it is possible to sort the sprites into groups by their optically perceptible characteristics. The general quasi-static as well as the dynamic properties of the electric field above the thunderstorms have primary role in the initiation, evolution and formation of sprites (Pasko, 2006; Asano et al., 2009a, 2009b). Observed characteristics of sprites, therefore, may refer to the properties of the electric field ambient to these TLEs if relationships among the features of these two elements of the mesospheric environment are explored and verified by observations and appropriate models. Information on the ambient electric field can be used further to infer the prevailing characteristics of the discharge processes both in the thundercloud and in the upper atmosphere. As a consequence, the charge distribution in the cloud and in the lower ionosphere can be inferred indirectly, too.

Classification of sprites is readily plausible by their shape (morphology), by the duration or optical lifetime of the events, by the number of individual light emitting elements per events, and also by characteristic temporal or spatial variations of the properties above. Concerning the morphology, there are a few characteristic forms of sprites which have been recognized after only a few early detections in the 1990s. Many scientific papers in sprite research concentrate only to the two most commonly identified types, i.e. to "carrot" (Winckler, 1997; Hardman et al., 2000; Su et al., 2002a; van der Velde et al., 2006) and to columniform sprites (Winckler, 1997; Wescott et al., 1998b; Hardman et al., 2000; Su et al., 2002a), although the description of various forms of sprites can be found in the literature. Other documented sprite forms include angel sprite (Stanley et al., 1999; Su et al., 2002b; Jing et al., 2008), tree-like sprite (Gerken et al., 2000), sprite-ball (Hardman et al., 2000), and wishbone or 'V' sprite (Moudry et al., 1998; Matsudo et al., 2007). Regarding the optical lifetime, great variability of this parameter has been observed. In terms of the number of conventional (de-interlaced) video frames (16.7-20 ms per field), some sprites have been recorded only on a single video field (i.e. within 20 ms) while others were found to last on more than 10 fields (>200 ms) (Lyons, 1994a, 1996; Hardman et al., 2000; Jing et al., 2008). Winckler et al. (1996) as well as Lyons (2006) noted that very bright sprites can have very short duration. By counting the number of individual elements in a sprite event, more observers pointed out that sprites (at least above continents) seem to appear more frequently in clusters rather than alone (Sentman et al., 1995; Stanley et al., 1999; Su et al., 2002a; Jing et al., 2008). Su et al. (2002a) noted that the fraction of sprite clusters was smaller among the events observed above water than among those observed above land. The physical background of this observation is yet to be explored. Lyons et al. (1994b) have reported first on a special type of multiple sprite emission, the so called “dancing sprite” (Moudry et al., 1998; Hardman et al., 2000). In dancing sprite events, individual sprites mostly of similar shape appeared one after another displaced from each other both in time and in space so creating the impression that one or few sprites “dance” across the sky. This group of events has been defined by the characteristic complex temporal and spatial variation of the appearance of the emissions.

Parallel to the observations, sophisticated models have been built in order to explain the documented characteristics of sprites (Pasko et al., 2012). The primary mechanisms behind the initiation and development of a sprite event are assumed to be the quasi-electrostatic (QE) heating due to the supercritical ambient quasi-electrostatic electric field (Pasko et al., 1997; Rycroft and Odzimek, 2010) and runaway air breakdown (Yukhimuk et al., 1998). The role of the electromagnetic pulse (EMP) of lightning discharges in sprite initiation has also been considered (Adachi et al., 2004). The formation, evolution as well as the spectral properties of streamers in sprites (Gerken et al., 2000; Stenbaek-Nielsen and McHarg, 2008) have been the target of extensive theoretical research (Pasko et al., 1998; Pasko, 2010; Chanrion and Neubert, 2008, 2010; Ebert et al., 2010). Fractal models are especially successful in describing the branching of streamer channels (Pasko et al., 2000; Hayakawa et al., 2007). Sprite simulations based on the above mentioned concepts (Taranenko and Russel-Dupré, 1996; Roussel-Dupré et al., 1998; Cho and Rycroft, 1998; Pasko et al., 1998, Hu et al., 2007; Hayakawa et al., 2007) usually give back the large scale structure of sprites well for subsets of the observations, but no unified theory accounts for all details of the observed features in complex events currently. It is plausible that details of directly observable sprite characteristics can help in validating and refining the existing sprite models, so some of the unconsidered features will be discussed in the present paper.

The tendency for sprites to appear in clusters was considered to be caused by horizontal lightning discharges, which act as a fractal antenna (Validivia et al., 1997). These discharges can generate regions of high electric field intensity above the thundercloud, and the emissions can be initiated quasi-simultaneously in these regions. In such cases, the configuration of sprite elements in a cluster and the locations of initiation may follow a pattern in the electric field intensity. This pattern can be formed by the superposition of the ambient electric field and the EMPs radiated by lightning discharges in the thundercloud or it can be an interference pattern among direct waves radiated by the source discharge current, waves reflected by the ground, and waves reflected by the ionosphere (Cho and Rycroft, 2001; Adachi et al., 2004).

Note that the same number and type of sprites can appear in rather different configuration in different events. The elements may be tightly packed or placed loosely. In some cases, sprites seem to be arranged in a circular or ring-like formation which mirrors the symmetry of the quasi-static ambient electric field above a more localized charge center in the thundercloud (Vadislavsky et al., 2009). At other times, the arrangement of sprites in a cluster seems to be random (Wescott et al., 1998b). Environmental parameters driving the configuration and actual location of appearing sprites are yet to be identified.

It is generally accepted that the final form of sprites observed by conventional frame rate cameras is the composition of time integrated traces of fast moving bright streamer heads advancing in the ambient electric field. Sprite emissions start with downward propagating bright positive streamers in most of the cases (Stanley et al., 1999; Gerken and Inan, 2002). As it appears on high-speed video records, this process was described as "confetti falling from sky" (Stenbaek-Nielsen and McHarg, 2008). One example of the rare upward initiation has been shown by McHarg et al. (2002). Following the initial process, the upper part of the channel of the initial streamer can re-brighten and it may extend (primarily vertically), and/or it can serve as starting point for other, upward propagating negative streamers (Gerken and Inan, 2002; Stenbaek-Nielsen and McHarg, 2008; Montanyà et al., 2010; Gamerota et al., 2011). Depending on the occurrence, intensity and evolution of these emissions, various shapes build up on the video frames with longer frame exposition times (16.7-20 ms per a video field in case of conventional, interlaced records).

The characteristic life time of streamer processes in the height of the emissions is only few milliseconds (Pasko, 2006). Therefore, streamers cannot be the source of the lasting glow of some (usually central) parts of the events which remain visible for tens of milliseconds as their emission has been observed on several consecutive video frames (Lyons, 1994a, 1996; Hardman et al., 2000; Jing et al., 2008). High-speed video records revealed that the appearance of such lasting emissions may follow the initial streamers with a time delay of about one millisecond, so these are in fact afterglows (Stenbaek-Nielsen and McHarg, 2008). Persistent emissions in sprites used to be attributed to photochemical processes of longer time constant (Sentman et al., 2008), but recent modeling has uncovered the possibility of a physical origin via ionization by electric currents in the body of the sprites and due to the consequent enhanced local electric field in the mesosphere (Luque and Ebert, 2010; Liu, 2010; Pasko et al., 2012).

This analysis is based on TLE observations in Central Europe, which have been performed mostly during the summer months in the years 2007-2009. In this period, there were only 55 nights on which local viewing conditions allowed optical observations to be carried out and both the hardware and an observer were ready to detect upper atmospheric emissions. The attempts to detect TLEs were successful on 28 nights. In all, more than 500 TLEs were recorded: mostly sprites (both with and without halos), standalone halos (Barrington-Leigh, 2000; Williams et al., 2012), few ELVES (Inan et al., 1997, 2010; Pasko et al., 2012), a blue jet-like event (Wescott et al., 1996, 1998a; Bór et al., 2009; Pasko et al., 2012), and two TROLL-like events (Lyons et al., 2000), too.

The analysis in this paper focuses on sprites which have the most varying form in the family of TLEs. Earlier efforts to classify sprites by optically perceptible properties are summarized and refining the classification is ventured according to the observations. This study focuses on directly observable properties: the shape of sprites, the number of apparently individual structures in an event, and the duration of the emission. Some peculiar details of well known, basic forms will also be described. Results of a preliminary analysis of this sprite observation set have been presented earlier (Barta et al., 2010). Based on the experience of that previous work, the dataset has been completely re-analyzed and this study is based on the latest results.

A brief overview about the instrumentation and about the method of observation is given in section 2. Scientific terminology related to the description of sprites is revisited in Section 3. Definitions of some general terms used throughout the paper are given and the adoption of general concepts to this study is described. Section 4 is divided into two main parts. In the first part, aspects according to which the morphological categories have been set up are discussed. The description of each morphological category is then provided together with a short review about the corresponding previous observations and modeling. The characteristics of various independent sprite features are summarized here, too. In the second part of section 4, the concepts of sorting sprite events into classes by the number and configuration of individual emissions are presented. Jellyfish and dancing sprites are introduced as special sprite clusters. Section 5 contains the results of the statistical analysis considering the type, number, optical duration, and the occurring sprite features in the involved events. This study is closed with the summary of the main conclusions in section 6. Some suggestions for directions of possible further research are given here, too.

2. Instrumentation, the observation site and the method of observation

The sprites in this study have been observed in Central Europe, up to a range of 500-600 km from Sopron, Hungary, where the detection system has been deployed. Sopron (47.68 °N, 16.58 °E, ~230m MSL) is located in the Western part of Hungary, near the Hungarian-Austrian border. The original instrumentation and methodology of the observations is summarized in another paper (Bór et al., 2009) so only the key hardware components are cited here, i.e. a Watec 902H2 Ultimate camera with Computar 8mm f/0.8 aspheric lens (horizontal and vertical field of views are 42° and 31°, respectively) and the UFO Capture real time event detection software (versions 2.15-2.22). Upon triggering, interlaced video clips have been recorded in 720x576 pixel resolution and at 25 frames per second, so that each de-interlaced video field covers 20 ms of time. The beginning and end of the exposure of every video field was marked by a GPS time inserter (KIWI OSD) with millisecond accuracy in UTC. In July, 2008 the camera was put in a fixed position and since then it is controlled remotely. During the observation period, the location of active thunderstorms was followed primarily by tracking the lightning flashes inside the viewing range. Maps of locations of lightning flashes have been provided by the LINET lightning location network (Betz et al., 2008) quasi-realtime. The actual map was refreshed at least once in every 10 minutes.

3. Definitions

Sprite: The term "sprite" (Sentman et al., 1995) is used to refer to optical emissions which originate from dielectric breakdown processes initiating in the form of streamers in the mesosphere (Stanley, 2000).

Sprite entity, sprite element: It was recognized early that sprites may occur as clusters of quasi-simultaneously appearing, distinguishably separate emissions of either simple (e.g. columnar) or more complex structure (Sentman et al. 1995). Members of these clusters are often called "sprite elements" in the literature (e.g. in Gamerota et al., 2011). Sprite elements, however, can be observed also singly showing practically the same forms as in clusters. Therefore, the term "sprite entity" is introduced in this paper to refer to an individual sprite element regardless if it appears in a cluster or alone. A sprite entity is defined as the whole emission structure the parts of which are in direct connection with the channel of a single "prototypical" sprite defined by Cummer et al. (2006). This means that the sprite entity is the ensemble of the emission from the initial streamer and all the follow up emissions the origin of which can be assigned to the initial streamer or to its channel. This definition is in agreement with high-speed camera observations where the formation of various shapes from the prototypical sprite can be clearly followed (Stenbaek-Nielsen and McHarg, 2008; Montanyà et al., 2010).

Sprite event: As per a straightforward definition, a sprite event consists of all sprite entities which appear in consequence of one parent lightning discharge. However, the current analysis is based on directly perceptible characteristics of sprites and identifying the causing lightning flash requires additional data from e.g. lightning detection networks. Since the parent lightning flash has not been looked up for all sprites in this study yet, a different definition of a sprite event was applied here. All those sprite elements were considered to belong to one event which appeared apparently close to each other in space and where later appearing additional elements were observed on consecutive video fields. If no additional sprite elements appeared at least for one video field (20 ms), any newly observed sprite elements were assigned to a different event. The relaxation time of the vertical electric field component above 60 km is less than 20 ms (Pasko et al., 1997), so it is generally safe to assume that successive sprites appearing with a time delay longer than this correspond to different discharge processes. Similarly, if two sprites appeared well separated, i.e. by more than about 50 km side to side from each other, they were considered as two separate events even if they appeared on the same video field or on consecutive video fields. The displacement of most sprites from their parent lightning flash was found to be less than 50 km (Lyons, 1996; Wescott et al., 2001; Sao-Sabbas et al., 2003), so separations larger than this generally indicate different source processes. The distance between sprites could be judged relatively easily by combining the direction of the event determined from the position of stars on the video frames with the position of thunderstorm cell(s) on the lightning map we used to align the camera. These criteria made the unambiguous determination and separation of events possible in the majority of cases. Note that the applied definition carries the possibility of counting sprites initiated by different lightning flashes as one event and separating sprite elements spawned by a single complex lightning discharge. The existence of such complex sprite producing discharges (Lang et al. 2010, 2011) requires to take the current definition of a sprite event pliantly e.g. in connection with dancing sprites (see the related discussion in section 4.2.2.). Nevertheless, a statistical approach based on a populous record set was used to examine the properties of sprite events in terms of the number of elements and in terms of the configuration of the elements, so the results are expected to mirror real trends.

Body of a sprite entity: In this study, "body" refers only to the ensemble of the brightest parts of a sprite entity as it appears on optical records of longer exposure times (Figure 1). In this view, a sprite entity consists of its body and other parts of less bright emissions occasionally occurring above and below it.

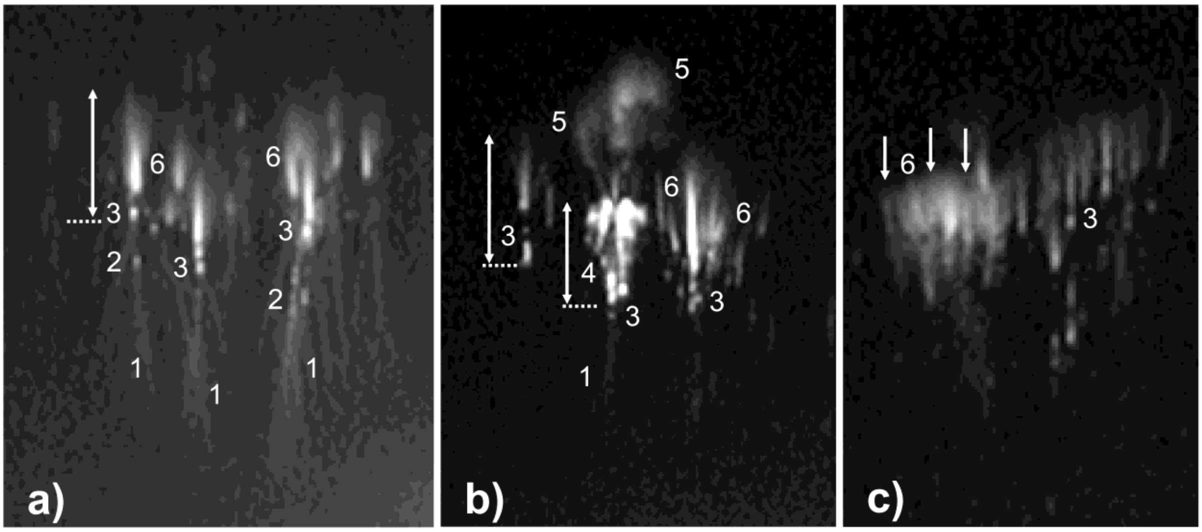


Figure 1. Sprites with various features: 1-tendrils; 2-beads along the tendrils; 3-spots; 4-beads in the sprite body 5-puffs; 6-glows. Double headed vertical arrows indicate the vertical extension of the body of the sprite entity on their right. Dotted horizontal lines show the base of the corresponding sprites. **a)** sprite cluster observed at 21:42:53.119 UTC, 10. June, 2009.; **b)** sprite cluster observed at 22:34:28.979 UTC, 02. Aug., 2009. A point-like as well as an elongated spot can be seen in the leftmost sprite element of the cluster; **c)** sprite cluster observed at 22:27:44.827 UTC, 02. Aug., 2009. Minor fluctuation of the brightness can be observed in the emission along the vertical directions shown by the arrows.

4. Classification of sprites

First, sprites are classified by their shape, and then by the number of sprite entities appeared during an event. The brightness and the duration of the emission are also directly perceptible properties of the events. However, our camera was not calibrated in the time period this paper concerns. Furthermore, the linear as well as the gamma gain level on the camera were varied especially in the first year to find optimal settings. Quantitative analysis of the radiometric intensity of the emissions, therefore, has not been investigated quantitatively. Apart from the non-constant gain settings of the camera, unequal atmospheric absorption and varying visibility prohibits the proper comparison of the observed brightnesses and optical durations.

On the other hand, camera settings were usually not changed dramatically, so the relative brightness of the events could be examined at least qualitatively among cases where the source-observer distances were similar. Apparent trends observed in the brightness of various sprites, therefore, will be noted.

Note that the brightness in sprites is determined by both the intensity and the duration of the emission at the given location. Similar image pixel brightness values can originate from a slower moving, less intense streamer head and from a faster but more intense discharge front. These properties, therefore, severely affect the detection of various morphological features as well as that of the sprite body. An undetected morphological feature on the records does not necessarily mean the actual absence of that feature; it can indicate fast streamers and/or low luminosity, too. Knowing the factors which determine the speed and brightness of streamer heads is, therefore, essential to be able to decide between the possible scenarios, and to avoid misinterpretation. Reising et al. (1999) showed that total sprite luminosity is linearly dependent on the electric current flowing through the body of the sprite. Liu et al. (2009) demonstrated the dependence of sprite streamers on the magnitude of the ambient electric field and they discussed the detectability issues of the streamers in relation with atmospheric scattering and settings of the detecting instruments. These findings should be matched with quantitatively analyzed optical sprite observations the investigation of the mesospheric environment to be possible on basis of such observations.

4.1. Classification by morphology

Sprite entities can be sorted into major morphological classes by considering their overall shape. Always the fully developed form of the emission was considered at the categorization. It can happen, however, that the full development of a sprite is recorded on two consecutive video fields even at lower capturing speed. In such cases it may seem as if the sprite was transforming or morphing. In such cases of virtually morphing sprites, the brightness peak-hold image created from the corresponding consecutive video fields was considered.

Major morphological classes were found to be: (1) columns, (2) wishbones and trees, (3) angel sprites, (4) carrots, and (5) other sprite forms. The naming of these classes refers to the final shape of the emission. These class names have been taken from previous notations in the literature. While various definitions published for the same morphological class were usually consistent with each other, mismatching descriptions were found, too. An example for this is the case of angel sprites, a naming that was introduced for different sprite shapes by different authors (Winckler, 1997; Stanley et al., 1999; Su et al., 2002b; Gerken and Inan, 2003; Jing et al., 2008).

A characteristically different sequence of general directions of streamer propagations during the formation of the event can be tentatively associated with the sprites in each class. The associated sequence of propagation directions of streamer-heads will be given at the corresponding class. Note that the given sequence of propagation directions has not been confirmed by high time-resolution video records for every class, especially for events in the angel class. Nevertheless, some details of the form of the emissions imply that streamers must have proceeded in the suggested directions in the suggested sequence. These telltale details will be described before the discussion of the characteristics of the major morphological classes.

Note that the classification was not possible when the image of an entity was too dim and/or too blurred. Such detections occurred in 88/489 events (18%). In most of the cases, the reason behind this was the combined effect of the large source-observer distance and the finite image resolution of the camera. Inaccurate setting of the focus of the lens and unfavorable viewing conditions also contributed to this effect. Sprite entities could not be analyzed also in cases when more sprite elements appeared in a tightly packed cluster and saturated the image so that individual elements could not be resolved. This was observed in 66/489 events (13.5%).

4.1.1. Occasionally observable sprite features

Classification of a sprite entity into a main morphological class reflects the overall form of the entity, which is primarily determined by the shape of its body, i.e. the region of the brightest emissions. Several additional morphological features of sprites exist, however, which do not show up with each and every entity even inside a main morphological class. On the other hand, rather similar features may be observed with sprite entities in more morphological classes. Note that the absence of these features on the images does not mean that they did not appear at all. It only means that even if they formed, their luminosity was below the detection level of the equipment.

4.1.1.1. Tendrils

Branched channels of the initial, downward moving streamer are often named “tendrils” (Figure 1) (Wescott et al., 1998a; Stanley et al., 1999; Stenbaek-Nielsen et al., 2000). Tendrils appear below the bottom of the sprite body as if they had “grown” out from it (Hardman et al., 2000). These channels are characteristically narrower than the bright upper/central part of the emissions and generally show high level of branching (Stenbaek Nielsen and McHarg, 2008). The visible length of the tendrils is varying as compared to the length of the sprite body and the length seems to be independent from the brightness of either the sprite or that of the tendrils themselves (Figure 1, Figure 2ef, Figure 8bd).

Sprite tendrils usually appear as faint filaments on the images but occasionally they can be rather bright as well. However, they are never as bright as the sprite body itself. For distant events, the tendrils below the sprite body may not be observed because of visibility issues. The color of the tendrils contains more emissions in blue wavelengths (Sentman et al., 1995) which makes them poorly visible from longer distances due to the enhanced scattering of photons on air molecules. The sensitivity of the applied camera is also lower at wavelengths below 400 nm (Yaniv et al., 2009).

Lasting afterglow of the central part of the sprite doesn’t extend into the tendril region. This observation support the idea that tendrils and sprite afterglows are produced by different physical mechanism (Luque and Ebert, 2010; Liu, 2010; Pasko et al., 2012). Tendrils are identified as traces of downward propagating and branching streamer heads of positive polarity (Gerken and Inan, 2002; Stenbaek Nielsen and McHarg, 2008). Tendrils are the manifestation of streamers in the sprite model of Pasko et al. (1998) in the form of branching filaments. Collective branching characteristics of streamers can be well described by fractal methods (Pasko et al., 2000), but physical factors driving the splitting of streamers are yet to be identified. A recent model by Luque and Gordillo-Vázquez (2011) suggests that streamer splitting can be caused by the destabilization of streamer heads due to local inhomogeneities in the electron density.

4.1.1.2. Beads/Spots

In the scientific literature, the term “sprite bead” is extensively used for localized bright spots appearing anywhere in sprites (Figure 1) (Stanley et al., 1999; Stenbaek-Nielsen et al., 2000). Sprite beads have been observed along the tendrils, inside the body, and at the bottom of the body but practically above the tendril region, too. This latter location is referred to as the “base” of the sprite (Figure 1) (Gerken and Inan, 2002). Beads observed along sprite tendrils have been reported to occur at streamer channel crossings, either at junction or at splitting points (Stenbaek-Nielsen and McHarg, 2008; Cummer et. al., 2006). High density of bright beads can be observed inside the body of some sprites (Figure 6cdg). These beads occur along channels of upward branching structures (Gerken and Inan, 2002, 2003). Note that bright bands or bands brighter than the rest of the underlying emission channel can be observed along the streamer channels in the body of simpler (i.e. column, wishbone, or tree) sprites, too (Figure 3bd). These regions are not necessarily dot-like; they can be elongated and they remain luminous for more consecutive video fields, too. Beads at the base of the sprite body (Winckler, 1997; Hardman et al., 2000; Stenbaek-Nielsen and McHarg, 2008) used to appear seemingly lined up in the direct continuation of the vertically elongated sprite body, whereas the beads along the tendrils can be somewhat more distributed also horizontally along the branched tendrils (Figure 1a). Note that the actual position of beads relative to each other and to other parts of the sprite cannot be fully judged from 2D images captured from one observation site.

While sprite beads can be static (Marshall and Inan, 2006), relatively slow upward drifting motion of those beads at the sprite base and inside the sprite body have been observed by more authors (e.g. Stanley et al., 1999; Stenbaek-Nielsen and McHarg, 2008). The speed of this upward motion was reported to be around 10^4 m/s (Gerken and Inan, 2002, 2003). Optical lifetimes longer than 100 ms have been found for sprite beads (Stenbaek-Nielsen et al., 2000; Gerken and Inan, 2002; Marshall and Inan, 2006). It can be also because of the relatively long standing emission that beads appear very bright on the captured images.

Beads appearing in different regions of sprites are speculated to have been created by different physical mechanisms the details of which are not well understood yet. For example, streamer splitting and merging are associated with bead formation along the sprite tendrils, but accepted models for the tendril region do not account for these processes. Beads in the sprite body are, on the other hand, more successfully interpreted by an analogy with beading in cloud-to-ground (CG) lightning (Gerken and Inan, 2002), where irregularities of the density and composition of the local medium play the key role. In case of sprites, electron density fluctuations as well as dust particles of meteoric origin (Zabotin and Wright, 2001) can cause the formation of beads. As for those beads observed at the base of sprites, one possible explanation of their appearance can be the passage of the initial sprite streamer through region(s) of enhanced electron density (Luque and Gordillo-Vázquez, 2011). Note that it has been observed, too, that a spot became visible only on the next video field after the one on which the sprite appears.

In this study, beads observed at the base of sprites were distinguished from other beads because they have specific properties. In what follows, these beads will be referred to as "spots" for clarity. Spots can be easily recognized in the studied set of records, whereas the high number of bright beads in the body of sprites can saturate the image which makes the actual structure of the sprite body unrecognizable. On the other hand, smaller, less bright beads along the tendrils are easily overlooked in blurry images of distant sprite events. The size and brightness of spots is usually superior to those properties of beads along the tendrils (Figure 1a). Spots can be observed also in cases when no tendrils are visible (Figure 2bc, Figure 5b, Figure 6b), so they are a rather frequently recorded feature. High-speed images support the idea that spots belong rather to the primary streamer channel than to the downward branches originate from it, and that spots are supposed to be inside the region where sprite afterglow occurs (Stenbaek-Nielsen and McHarg, 2008, Figure 9).

The number of spots observed at the base of a sprite entity varies from one to 4-5. Spots are separated from the sprite body and from each other by dark bands (Hardman et al., 2000). Point-like spots or spots having a fairly circular outline were observed in the majority of cases, while it could be observed in 81 of all 305 events featuring spots that the spot was more or less oval or even elongated (Figure 1b, Figure 2c, Figure 6b). Elongated spots can either indicate the presence of a thick region of enhanced electron density, or may be the result of a short lived but faster upward spot propagation. Upward propagation of spots has been in fact observed in some of the examined Central European records, too. Nevertheless, spot propagation and its relation with other directly observable sprite properties was not analyzed in detail in the framework of this study, therefore, it is a subject of future research. Note that not all elements in a sprite cluster necessarily have spots. On the other hand, circular as well as elongated spots may be observed simultaneously below the body of the same sprite (Figure 1b, Figure 2c).

4.1.1.3. Puffs

A sprite feature observed most frequently with carrot sprites is the appearance of one or more diffuse “smudge” emissions or puffs (Figure 1b) above the body of the sprite (Stenbaek-Nielsen and McHarg, 2008). These puffs are always in the high altitude range of sprite emissions (> ~85 km). This form of emission is well described by the model of Pasko et al. (1998). According to this model, the time scale of dissociative electron attachment is larger than the time scale of dielectric ambient relaxation time in this altitude region, so individual electron avalanches cannot transform into streamers here. Fitting into this view, puffs are usually well separated from the body of the sprite. If the body is at lower heights, emission channels can connect it to the puff(s). If any connecting emission channel is visible, it becomes more and more diffuse before it would extend and end in the extended puff with a smooth transition (Figure 1b). Note that this connecting channel is usually less bright than the body of the sprite. High-speed recordings showed that puffs unambiguously correspond to upward developing structures (Stenbaek-Nielsen and McHarg, 2008; Montanyà et al., 2010).

4.1.1.4. Glows

Diffuse glows are, on the other hand, sometimes observable around the central body of sprites in height regions where streamers can appear, too (Figure 1) (Gerken and Inan, 2002, 2003). These “glows”, as they will be referred to in what follows, surround the body of the sprite in a way that the glow toward the upper end of the sprite body is always more extended resulting in an overall bulb-like shape. Such a glow may start to appear only at some height along the sprite body. When such glow is present, the emission of the central part itself becomes more diffuse with the growing height, so the top terminating altitude of the event cannot be determined unambiguously. Sprites with this feature have possibly been characterized in previous reports as those having “hair” (Sentman et al., 1995; Jing et al., 2008). In other cases, however, a bulb-like shape cannot be unambiguously associated with the glow (Figure 1c). Gerken and Inan (2002) observed an upward motion of some glows. The speed of the motion was found to be similar to that of moving spots, i.e. $\sim 10^4$ m/s. Glows in the sprite images can be identified and distinguished from puffs by their characteristic bulb-like shape and/or by that they are accompanying the bright sprite body rather than occurring above it, separated.

Glows around the upper section of the bright sprite body may indicate that these emissions are at a height of ~80 km, in the transition zone between the streamer formation region and the region of diffuse glow discharges (i.e. puffs) (Pasko et al., 1998; Gerken and Inan , 2002). The glow around some sprites, on the other hand, can be an independently produced glow discharge maintained by an enhanced electron density in pre-existing streamer channels (Gerken and Inan, 2002; Luque and Ebert, 2010), or a re-brightening of a preceding sprite halo in the corresponding region. A sprite halo has been in fact preceded or observed together with 19 sprites out of the 149 events featuring glow emission in the examined dataset. (The total number of recognizable halos which were followed by sprites was 39.) The reasons of missing a sprite halo with a conventional camera can be the short duration (< 2 ms) of this type of TLE, the finite sensitivity of the recording system, and the non-optimal triggering settings at the detection (Bór et al., 2009; Williams et al., 2007, 2012).

Gerken and Inan (2002) reported the frequent presence of horizontal "striations" in the glowing region. They discussed that such striations may occur due to sinusoidal charge density variations along the field lines. These charge density variations make the appearance of the glow discharges possible in ambient electric fields lower than those required for a homogenous glow discharge. The phase of the striations moves in the direction of the ambient electric field as electrons diffuse. The group velocity of the striations, at the same time, points in the opposite direction, which can explain the upward motion of the glows on some records.

4.1.2. Column sprites (columniform sprites, c-sprites)

In the literature, a "columniform sprite" is described as a bright, vertically aligned, elongated light emitting column, the diameter of which is ranging from tens of meters to a few hundred meters at ~60-85 km altitude (Gerken et al., 2000; Wescott et al., 1998b; Hardman et al., 2000; Stanley et al., 1999; Su et al., 2002a; van der Velde et al., 2006) (Figure 2). The reported length of the columns is around 10-15 km in most of the cases (Wescott et al., 1998b), but apparently very short lengths can be observed, too. It is possible that the "sprite ball" noted by (Hardman, et al., 2000) is in fact an extremely short column sprite. The body of the column sprite is probably defined by the afterglow of the trail of the downward moving streamer head (McHarg et al., 2007).

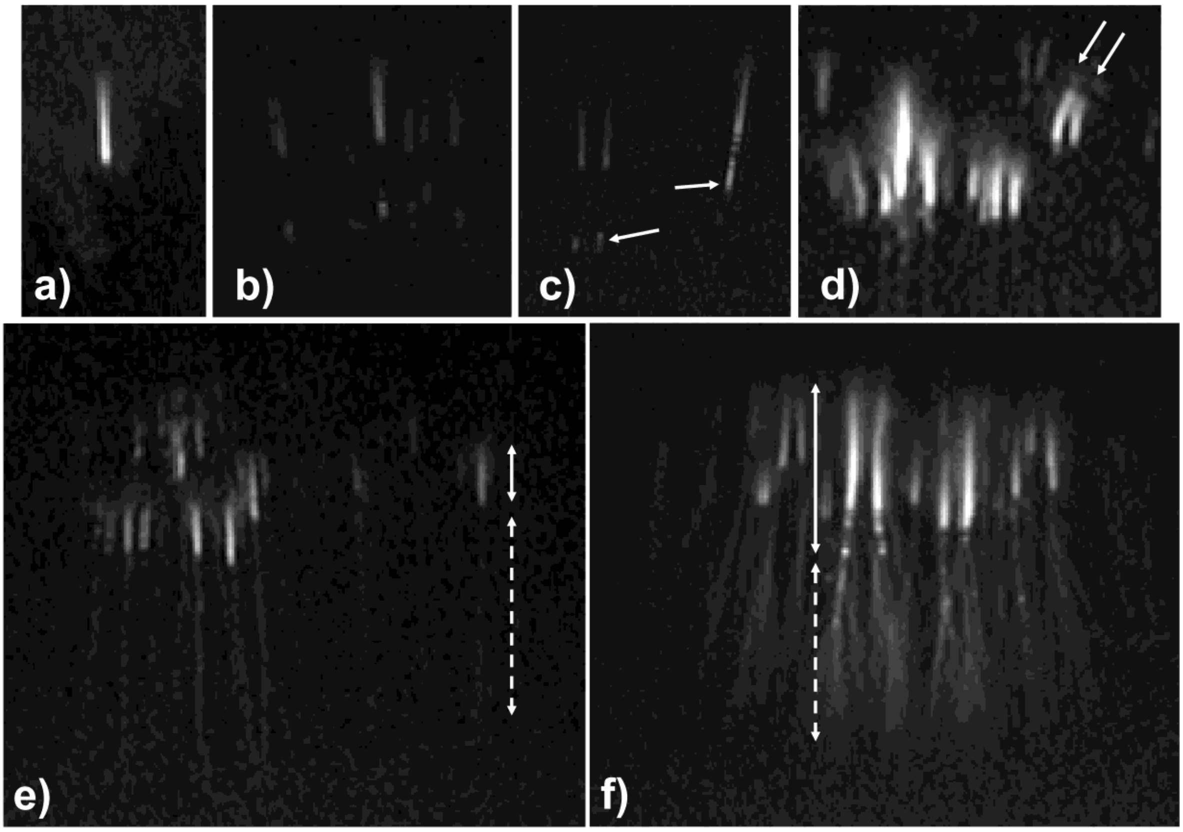


Figure 2. Column sprites observed in Central Europe. In the d) and e) images, the solid double headed arrows show the vertical extension of the body, while the dashed double headed arrows indicate that of the tendrils of the brighter sprite to their left and right, respectively. **a)** 01:37:03.251 21:42:53.119 UTC, 07. July, 2007.; **b)** 23:45:28.004 UTC, 02. Aug., 2009.; **c)** 22:08:41.113 UTC, 02. Aug., 2009. The arrows point at elongated spots; **d)** 22:37:37.484 UTC, 02. Aug., 2009. The arrows point at puff-like features; **e)** 21:54:57.069 UTC, 02. Aug., 2009.; **f)** 23:08:54.879 UTC, 02. Aug., 2009. Bending and tilting of individual sprite elements can be observed on the left and right sides of the double headed solid arrow.

In the majority of cases, column sprites are aligned vertically and members of column sprite clusters appear parallel (Figure 2abde). Since the propagation of streamers is guided by the ambient electric field, the orientation of sprites indicates the prevailing direction of field lines. Above the parent lightning flash at sprite initiation altitudes of 70-80 km the field is practically vertical as it is mirrored by vertical and parallel orientation of most sprites. Closer to the underlying thundercloud, electric field lines bend towards the lower charge center. This is the best demonstrated by long tendrils in cases when the displacement of the sprite from its parent lightning flash is larger. Such tendrils have been observed to bend as they follow the running of the electric field lines (Stenbaek-Nielsen et al., 2000). Such situation occurs with various sprite types (Figure 6l, Figure 8ad).

Rarely, some members of a column sprite cluster are not quite parallel with the others (Figure 2df), and it was observed that the direction of a column sprite can significantly deviate from the vertical (Figure 2c), or from the direction of other elements in a cluster. Such phenomenon has been observed also by Stenbaek-Nielsen et al. (2000). In the currently analyzed record set, this was observed only in 16 events. The presence of tilted and/or non-parallel sprite elements can indicate a more structured background electric field. This non-regular electric field can originate from a more extended and complex tropospheric source and/or it can appear because of lower-ionospheric irregularities. Note that the local electric field can be distorted considerably due to the sprites themselves, too.

Only downward propagating streamers have been observed with columniform sprites (Stenbaek-Nielsen and McHarg, 2008). These streamers are initiated at heights about 70-80 km (Gamerota et al., 2011). The criterion according to which events were sorted into the “column” class is the lack of any sign of upward propagating and/or branching structures in the central, brightest part of the sprite.

Except for puffs, all occasionally observable sprite features may appear with column sprites, theoretically. In practice, however, a puff was seen above the column (Figure 2d) in 2 cases and in 5 additional cases it could not be unambiguously decided if the emission was a puff or an extended glow. In lack of evidence for the opposite case, these cases were listed as columns with puffs. Such sprites may have been caused by double headed streamers (Luque et al., 2008a; Qin et al., 2012), but these elements could have been misclassified, too. They can be either overlapping events or wishbone sprites seen from the side. Regarding spots, the apparent distance of the (topmost) spot from the column varied considerably. Observed separations ranged from those smaller than the width of the corresponding column to gaps 10-15 times the width of the corresponding column. Separations larger than 5 times the width of the corresponding column (Figure 2bc) were recorded only in 11 events. The separations were usually very similar within a cluster (Figure 2bcf).

Column is probably the simplest shape for a sprite and this form is probably the one the characteristics of which are the most successfully modeled to this date (Luque and Ebert, 2010).

4.1.3. Wishbone and tree sprites

In contrast to columniform sprites, also upward branching structures can be observed in other sprite events. If there are only two distinct branches without any special features, the shape is called a "V" or a "wishbone" (Figure 3be) as the form often closely resembles that special bone of the chicken. In some cases the shape is more like a "Y" (Figure 3ab); still it will be called a wishbone for simplicity. It must be noted, however, that these sprite elements do not necessarily have a vertical axis of symmetry. If there are more of the simple, well distinguishable upward branches, the structure is referred to as a "tree" (Figure 3bc). Reaching higher from the branching points, the obliquely running branches are bending upwards to become more and more parallel with the usually vertical initial streamer channel. This is the most noticeable with longer branches (Figure 3c). This observation is consistent with that of Cummer et al. (2006) who noted that streamers tend to bend to existing streamer channels. Sprite elements in this category have few branching points and two or at most three upward branches. Furthermore, the branches rarely fork or bifurcate again. Sprites with "V" or wishbone shape have been noticed in the events observed around Japan (Matsudo et al., 2007; Myokei et al., 2009), and in North America (Moudry et al., 1998). In North America, also tree-like sprite elements have been described (Gerken et al., 2000).

Wishbone sprites can be formed via different physical mechanisms. The upper part of the "Y" form in some wishbones, for example, can be simply the lowest region of the destabilizing ionization front the initial sprite streamer is developed from (Luque and Ebert, 2009). A junction point of streamer channels in the body of sprites may arise from upward moving secondary negative streamers starting from the pre-ionized and negatively charged channel of the initial, downward moving streamer (Stenbaek-Nielsen and McHarg, 2008; Luque and Ebert, 2010). The point of junction of streamers, on the other hand, can also be the point where a later initiated positive sprite streamer is attached to the negatively charged channel of an earlier streamer. Merging of streamer channels has been observed in laboratory experiments (Nijdam et al., 2009) and was described by electro-dynamic models (Luque et al., 2008b), too. Earlier observations have already triggered the idea that the electric field of the heavily ionized body of sprites can distort the originally more or less vertical local ambient electric field (Gerken et al., 2000; Gerken and Inan, 2002), so the role of the structure of the local field in the formation of sprites in general should not be overlooked. In absence of a large number of high-speed observations, the dominance or the absence of either production mechanism cannot be confirmed in the production of wishbone sprites.

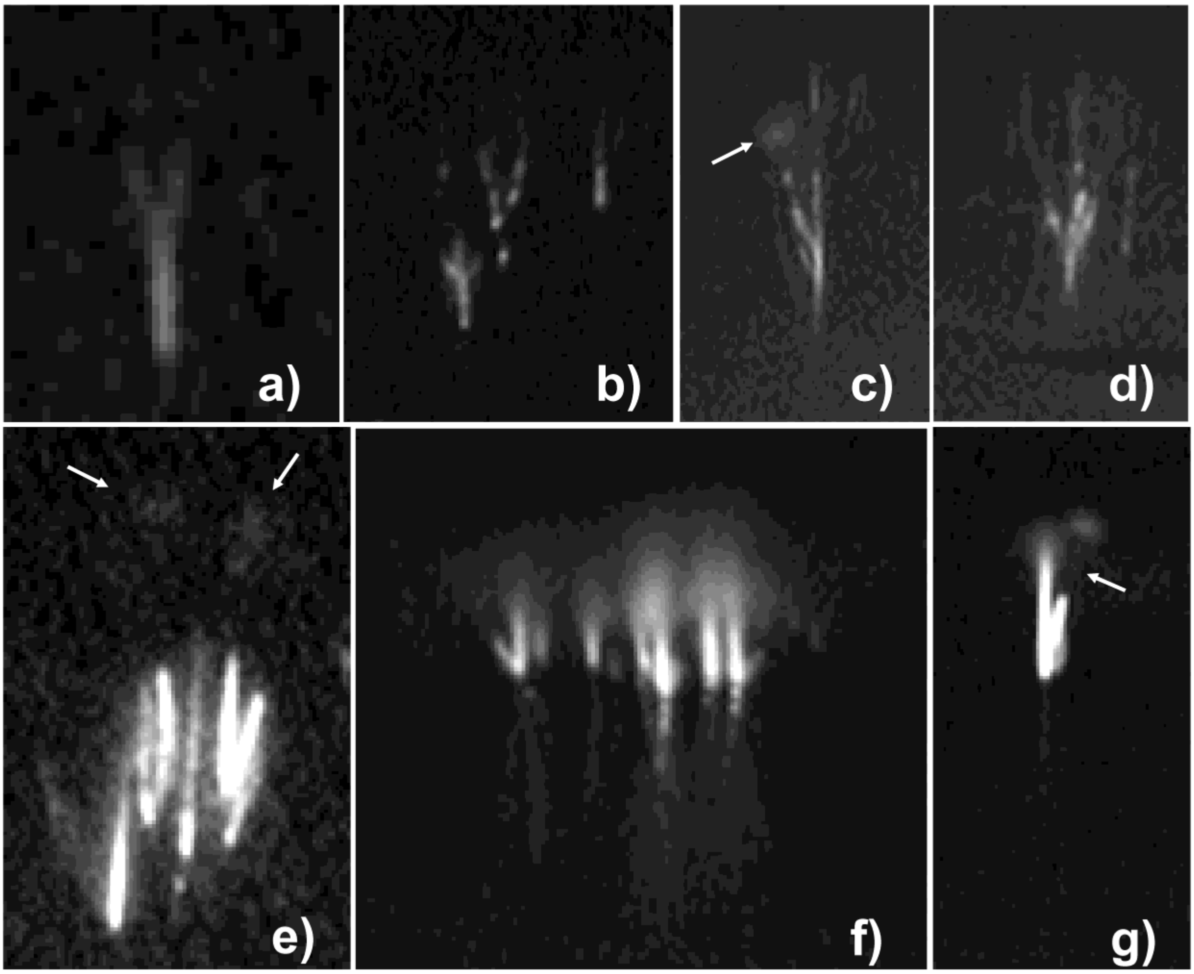


Figure 3. Wishbone and tree sprites observed in Central Europe. **a)** 01:15:21.108 UTC, 22. July, 2007.; **b)** 21:44:53.059 UTC, 07. Aug., 2008.; **c)** 22:13:10.710 UTC, 10. June, 2009. The arrow points at a puff; **d)** 21:48:20.448 UTC, 10. June, 2009.; **e)** 21:51:03.773 UTC, 10. Aug., 2007. The arrows point at faint puffs; **f)** 23:56:03.142 UTC, 02. Aug., 2009.; **g)** 20:25:02.567 UTC, 31. Aug., 2008. The arrow points at the faint section connecting the side branch and the corresponding puff.

It follows that both purely downward and downward-followed-by-upward streamer propagation directions can theoretically be assigned to this class of sprites. Since similar emission forms may build up as a result of different processes, sprite events in this morphological class may further be sorted into subclasses. Characterization of possible subclasses is, however, beyond the scope of the current analysis.

Among the various sprite features, spots may show up below the emissions in this category, too (Figure 3f). Large separation between the sprite body and the topmost underlying spot (i.e. separations greater than 5 times the smallest apparent width of the sprite body) has been noticed with less than 5 wishbones in the whole database. Tendrils and bulb-like glow emissions described with column sprites have been observed also with wishbones and trees, but only when the body of the sprite was brighter.

A feature that definitely appears with sprites in this class but practically hardly can be observed with columniform spites is the appearance of one or more puffs above some events (Figure 3ceg). A puff may appear above a branch, but may not all upward branches of a sprite element show this feature. If the puff is connected with its parent branch (Figure 3g), the connecting (fainter) emission section can be curved as it follows the arc of the sprite branch. According to our observations, however, a connecting emission section between the puff and the corresponding side branch could be observed only in 5 cases from all 40 events containing wishbones with puffs.

It must be noted that on images recorded from a single observation site, different emissions can be misidentified as wishbones or trees. One or more quasi-straight but slant emission sections can appear near the body of a sprite (Cummer et al., 2006). Although these sections are rather close to the body of the sprite they do not seem to be directly connected with it (Figure 4). Another example for this phenomenon can be seen in Figure 2 in Cummer et al. (2006). The question whether these emissions are standalone air discharges in the local electric field of the “parent” sprite elements or they originate from secondary streamers starting from the existing channel of the primary sprite streamer cannot be answered based on low frame rate observations. When independent emissions overlap with a column, they can create the false impression of branches from a certain viewing angle. It is also possible that column sprites of different orientation are produced during the video field integration time. If such columns overlap they can be misinterpreted as a wishbone or a tree. Furthermore, variations of the local electric field or variations of the ambient medium (e.g. neutral and/or electron density) (Moudry et al., 2003) may result in the distortion of the channel of the initial streamer. Again, it is the overlap of different sprite elements which can cause an erroneous classification is such cases. The question whether an event was a true wishbone or a tree can be answered sometimes only by higher resolution stereoscopic observations. Higher resolution refers both to the temporal and to the spatial resolution of the imaging.

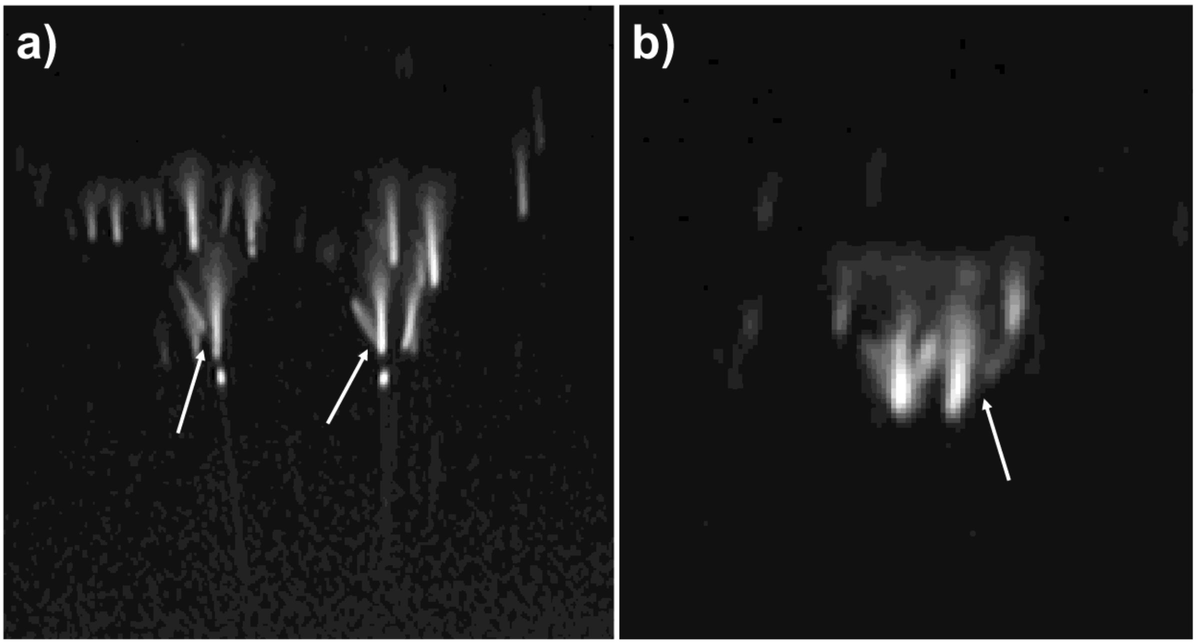


Figure 4. Sprites with non-connecting side emissions. The arrows point at seemingly not connecting side branches. **a)** 21:36:48.997 UTC, 02. Aug., 2009.; **b)** 21:12:51.648 UTC, 10. June, 2009.

4.1.4. Angel sprites (bird sprites)

Sprites with angel-like shapes have been reported earlier by more authors but the given definitions do not agree. The notation by Winckler (1997, Fig. 5.) agrees with the definition given by Stanley et al. (1999) and by Su et al. (2002b), i.e. “An ‘angel’ sprite also has tendrils, but the head is capped by a diffuse glow”. This description corresponds more to events which are rather called “jellyfish” sprites recently (Pasko et al., 2012). On the other hand, Jing et al. (2008) mention “columns with angel-like wings” which fits to the most recent characterization by Pasko et al. (2012): “… angel sprites which are bifurcated columns with bright channels extending diagonally”.

This recently published description will be adopted in this paper. In this view, the shape of sprite events in this class differs practically only in one important detail from the shape of tree or wishbone sprites. For members of this category, upward forking branches seem to brake sharply downwards and away from the central line of the figure, similarly to open wings of a bird or an angel (Figure 5). Note that not only the primary upward branches can band toward the central column but the end of the downward pointing sections of the wing can bend in the same direction, too. This has been observed only once in the analyzed record set observed from Sopron (Figure 5d), but the phenomenon can be clearly seen in other records also from Central Europe (Figure 5e). A central column is usually visible, so these sprites develop more frequently from trees. In most of the cases two wings can be observed on both sides of a central column, but it also happens that the break-down on the branch (i.e. a full wing) can be observed only on one side of the emission (Figure 5d). The observed luminosity of these events is different, but according to our experience angel sprites are among the brighter sprite events.

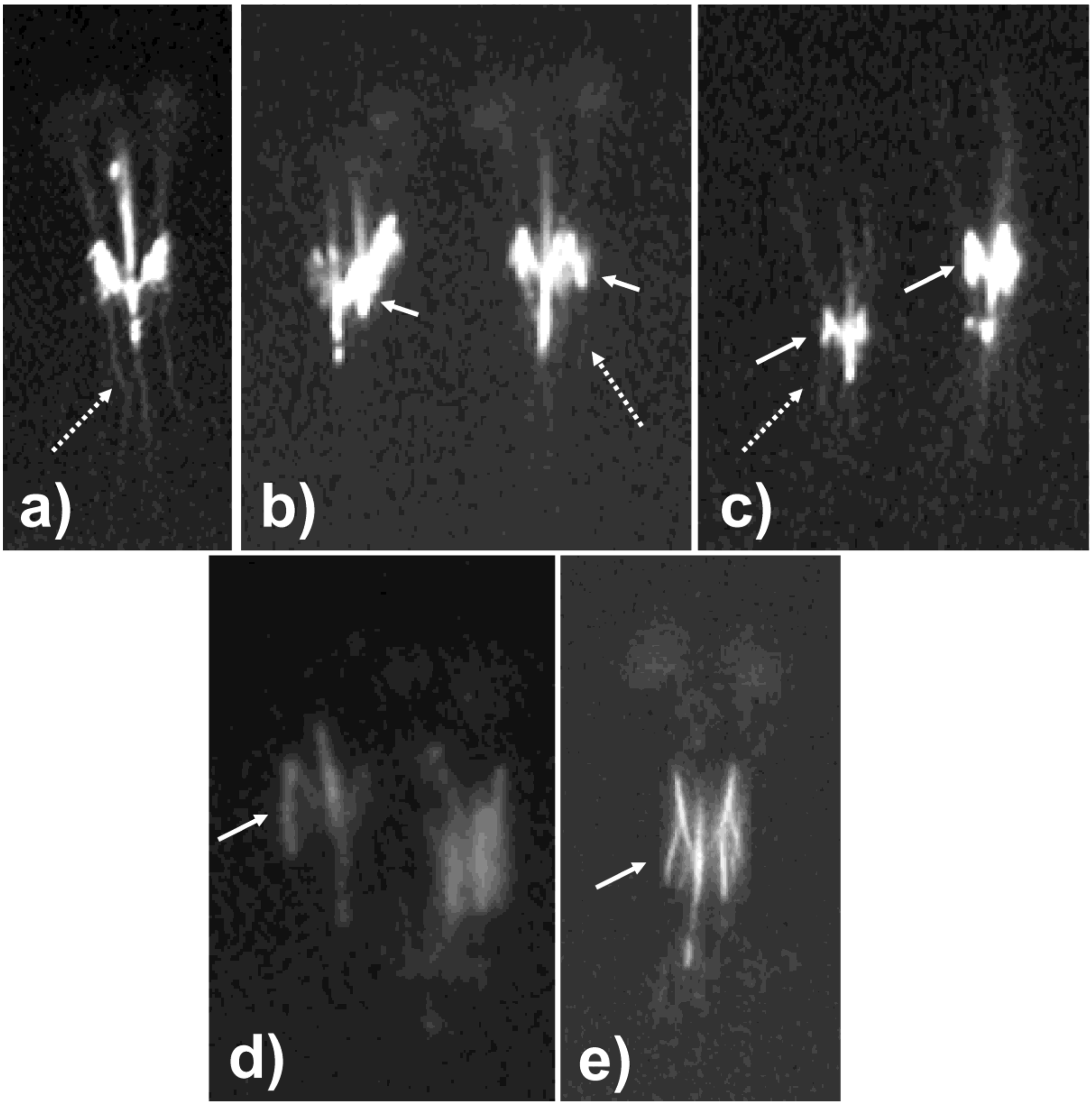


Figure 5. Angel sprites observed in Central Europe. Solid arrows point at the downward pointing end of wings, dotted arrows point at filaments attached to the end of downward pointing streamer channels. **a)** 21:46:02.113 UTC, 02. Aug., 2009.; **b)** 22:56:42.893 UTC, 07. Aug., 2008.; **c)** 21:08:50.446 UTC, 07. Aug., 2008.; **d)** 20:00:12.896 UTC, 10. Aug., 2007. This event appeared behind thin clouds.; **e)** around 20:39 UTC, 02. July, 2012. Courtesy of Martin Popek.

Tendrils are frequently visible below the central column of angel sprites. In addition to these, filaments may appear in the continuation of broken down branches, i.e. at the ends of the wings, too (Figure 5abc). Although the bottom of the bright wings seems to lay higher than that of the central column, the filaments are similar to tendrils, i.e. they are thinner and fainter than the wing or the central part of the sprite. On the other hand, bulb-like glow emissions were not unambiguously observed together with angel sprites. One or more spots, however, can be observed below the central column similarly to the previously described classes. These spots bear the same characteristics as those appear below some columniform, wishbone or tree sprites described above, but the separation of spots from the central body is observed to be small for angel sprites. With some instances of angel sprites, puffs can be observed at greater height above the central column and at about the same height in the continuation of the upward branches (Figure 5ab). These glowing patches are usually connected with the corresponding lower bright part by a fainter section or arc as it was described at tree sprites.

The simultaneous presence of puffs (which correspond to upward propagating streamers) and additional filaments under the downward pointing end of the wings suggests that the direction of streamer propagation in fact changes from upward to downward in the wings. The sequence of propagation directions is supposed to be down, up, down in the initial streamer and in the wings, respectively. Streamers propagating in these directions are assumed to build up the initial streamer channel, the upward pointing side branches, and the downward pointing ends of the wings, sequentially. No theoretical work has been found in the literature to this date which addresses the modeling of these structures.

4.1.5. Carrot sprites

Every sprite that has a body more or less resembling a carrot-root can be called a “carrot” sprite (Figure 6). The upper section of such a form is generally wider and the diameter of the body generally shrinks at lower heights. Carrot sprites are noticeably thicker than columns, nevertheless the length/(maximum width) ratio of the body showed considerable variation in our dataset (Figure 6ah). In certain cases, tendrils are visible below the central body. These can represent radicles of a carrot root. The picture can be completed by one or more straight or curved emission sections connecting to the top of the central emission (i.e. to the carrot root) and ending in a diffuse emission cloud (a puff) at their tops (Gerken et al., 2000;

Hardman et al., 2000; McHarg et al., 2007; Stenbaek-Nielsen and McHarg, 2008). These create the impression of stem and leaves of carrots. According to this view, at least one of the sprites recorded during their first documented observation in the scientific literature was certainly a carrot sprite (Franz et al., 1990). In this study, all sprites having a central part which resembles a carrot-root were sorted in the morphological category of carrot sprites, regardless the visibility of tendrils or upper emission sections and puffs.

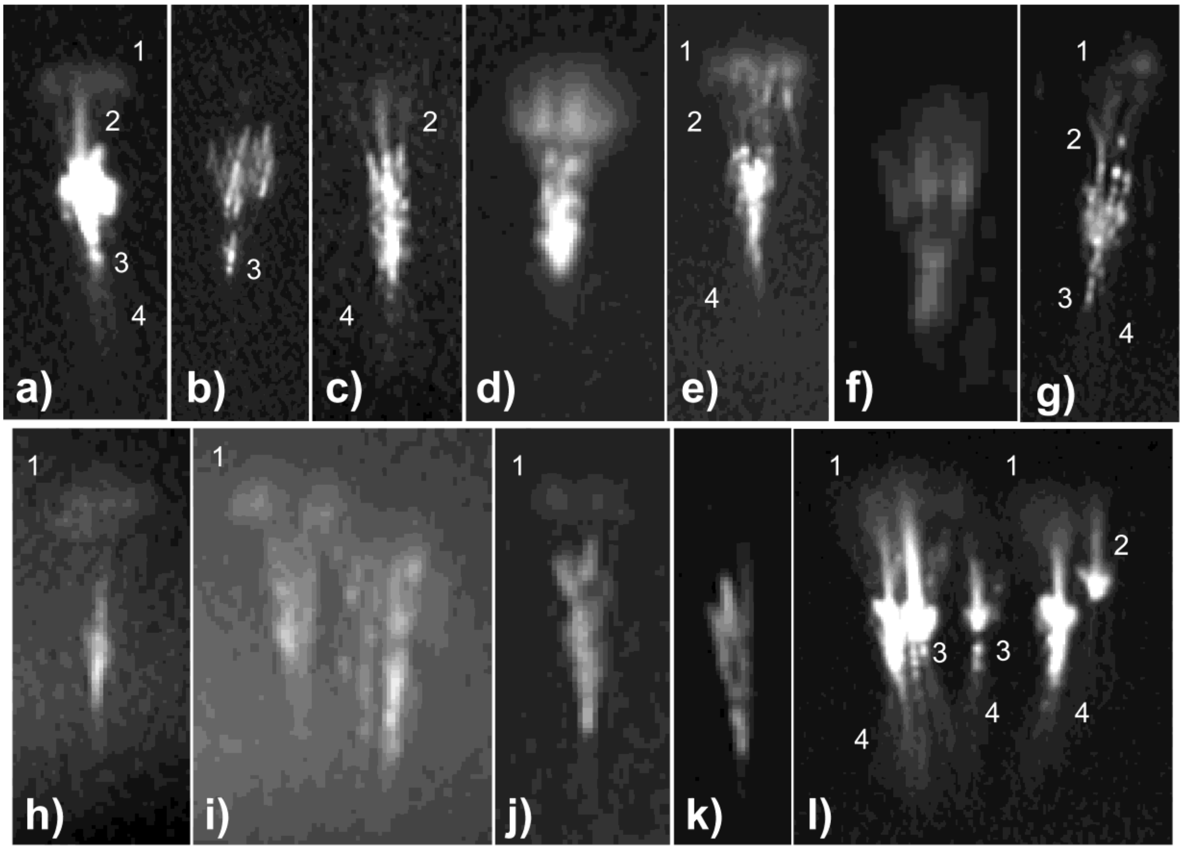


Figure 6. Carrot sprites observed in Central Europe. Occasionally observable carrot sprite features are indicated by numbers: 1-puff (leaves), 2-emission sections above the body (stems), 3-spots, 4-tendrils (radicles). **a)** 20:58:45.652 UTC, 21. July, 2007.; **b)** 21:36:43.838 UTC, 10. Aug., 2007.; **c)** 02:02:35.780 UTC, 15. June, 2009.; **d)** 00:51:18.259 UTC, 11. June., 2009.; **e)** 22:22:16.746 UTC, 10. June, 2009.; **f)** 22:51:51.618 UTC, 30. July, 2007.; **g)** 22:49:50.685 UTC, 02. Aug., 2009.; **h)** 01:42:38.447 UTC, 11. June, 2009.; **i)** 01:42:38.567 UTC, 11. June, 2009.; **j)** 22:15:34.814 UTC, 10. June, 2009.; **k)** 00:06:28.521 UTC, 03. Aug., 2009.; **l)** 21:38:01.749 UTC, 07. Aug., 2008. Lower sections of tendrils are bent as they follow the electric field lines.

The first description of this complex emission shape was given by Sentman et al. (1995): “A ‘carrot’ sprite is characterized by a relatively bright head region, typically at 66-74 km altitude, wispy structures (’hair’) extending above the head and bluish tendrils below”. All observations agree in the height range of the central (“head” or carrot root) region and that the puffs at the top of carrot sprites are usually in the altitude of 80-90 km, while the tendrils can reach down to 40-50 km (Sentman et al., 1995; Winckler, 1997; Stanley et al., 1999; Jing et al.,2008).

After observations with high-speed video cameras, Stenbaek-Nielsen and McHarg (2008) concluded that carrot sprites are sprites with both downward and upward propagating streamers. These sprites start out as column sprites, but subsequent upward propagating streamers (also named as upward developing structures UDSs, (Stanley et al., 1999)) complete the formation of the shape as it appears on conventional frame rate video records. This simple view of first downward, then upward propagating streamers in carrot sprites is supported also by more recent high-speed video observations (Montanyà et al. 2010). This sequence of propagation directions is the same as in cases of wishbone and tree sprites. The characteristic difference between the two categories is the significantly higher level of branching of the upward developing structures possibly accompanied with intense beading inside the body of the sprite.

Upward moving and spreading streamers can indeed form a cone-like shape resembling a carrot-root. Some carrot sprites, however, show deviations from the simple cone shape. The upper part of the cone can suddenly become wider which suggests that the streamers forming the body of such carrot sprites may have propagated in more directions with probably considerable horizontal components (Figure 6ab). Indeed, there is no reason to think that the sequence of alternating streamer propagation directions observed in angel sprites cannot continue (Figure 6b). In some other cases, the body of these sprites does not resemble a classic carrot shape very closely (Figure 6cdf). The structures in the body of carrot sprites are hard (sometimes impossible) to resolve in low frame rate records due to the high density of streamer channels (Gerken et al., 2000), because of the high speed of the propagating streamer heads (Marshall and Inan, 2005), and also because of the intense emission, which saturates the observation system in many cases.

Another difference among the observed carrot sprites is manifested in the structure of the region immediately above the carrot-root. While emissions have not been always observed above the bright carrot body, they can be rather different if they are visible. In most observations, the region above the carrot body contain simple structures i.e. few straight sections or arcs (i.e. the “stems”) similarly to tree or angel sprites with puffs (Figure 6acgl). In another fraction of observations (16 of 87 events with carrots featuring puffs) several, occasionally branching streamer channels, upward stretching tendrils are seen (Figure 6de, and see also Figure 3 in Su et al., 2002a).

The differences in the observed forms of carrot sprites suggest that more source mechanisms can play a role in the formation of this shape. These differences indicate that the category of carrot sprites may not be a uniform class. It can consist of events created by more types of source processes or by various combinations of different source processes. Finding common characteristics of all carrot sprites, therefore, may not be always successful, since more variants can easily be mistakenly identified as a general carrot sprite if they have been captured from a larger distance and by a lower resolution camera. The identification of source mechanisms requires the verification of the existence of the possible subclasses of carrot sprites. This can only be achieved by more high-speed video observations in high optical resolution.

In addition to the possibly differently formed variants, misclassified tree or angel sprites among carrots may also hinder finding common characteristics of carrot sprites. Distant tree or angel sprites observed with lower resolution equipment in poor viewing condition can easily be classified as carrots (see e.g. Figure 3d). This emphasizes the importance of using appropriate imaging tools and the role of careful selection of events to be included in an analysis.

There are observations in which only the central carrot-root (i.e. the sprite body) is visible in the video frames. Tendrils, puffs, upper emission sections or upward branches do not necessarily show up with carrot sprites (Figure 6bk), even if the event was captured fairly close to the observation site. Even when they appear, the brightness of these features is generally lower than the brightness of the carrot body. Tendrils could be observed with carrot sprites only when also some of the emissions above the bright central part were visible. Puffs sometimes appeared without any visible “stems” (Figure 6j) and stems could also be observed without a diffuse “smudge” above them, too (Figure 6c). Similarly to sprites in all previously described categories, carrot sprites also feature one or more bright spots just at the carrot body slightly separated from the upper part (Figure 6abgl). Large separation of the (topmost) spot from the rest of the sprite body was not observed in carrot sprites.

Unique phenomenon in this class is the occurrence of beads recognizable also on conventional frame rate records inside the carrot body (Figure 6cdegi). These bright circular patches are similar to those beads which appear along the tendrils below the central part of the event (Winckler, 1997) and they can remain luminous for several tens of milliseconds. The formation and presence of beads in the carrot body are most apparent on high-speed video records (Cummer et al., 2006; Stenbaek-Nielsen and McHarg, 2008). Some of these beads are visible for longer time than the afterglow of streamer channels. Beads are most frequent in the widest part of the carrot body where the emission can remain observable on more consecutive video fields (also at conventional speed).

Existing models of sprite formation account for specific properties of carrot sprites, while they cannot explain other characteristics. Horizontal layers in these emissions i.e. the lower streamer structure (tendrils) as well as the upper diffuse emission region are well described in the quasi-electrostatic discharge model (Pasko et al., 1998). The characteristics of branching of the streamers are well simulated by fractal models (Pasko et al., 2000; Hayakawa et al., 2007). The general form of the carrot-root, however, is more closely approximated in the framework of runaway electric discharge models (Taranenko and Roussel-Dupré, 1996; Roussel-Dupré et al., 1998). On the other hand, no well established theoretical background exists which describes the occurrence of beads inside the carrot body or the variation of the form of the carrot body itself.

4.1.6. Other sprite forms

Despite of the fact that most of the observed sprites can be sorted into the morphological classes defined above, there are some events which have a shape that does not fit unambiguously into any of the discussed categories (Figure 7abc). The directions of streamer propagation usually cannot be inferred unambiguously in these sprites. Sprite forms similar to that in Figure 7b have been observed in 10 events. This kind of emission is widening with the growing height and it does not seem to have any inner structure, as if practically all of it resided in the upper zone of diffuse emissions (Pasko et al., 1998). Figure 7ef shows a peculiar tree-angel hybrid form, where additional quasi-simultaneous bi-directional discharges can be observed. All these events were put in the "other" category. The formation of these emissions has happened possibly under peculiar conditions regarding the structure and dynamics of either the high altitude electric field or the ambient medium. Another explanation for some irregular shapes can be that the image is formed by more overlapping sprite elements of previously defined types.

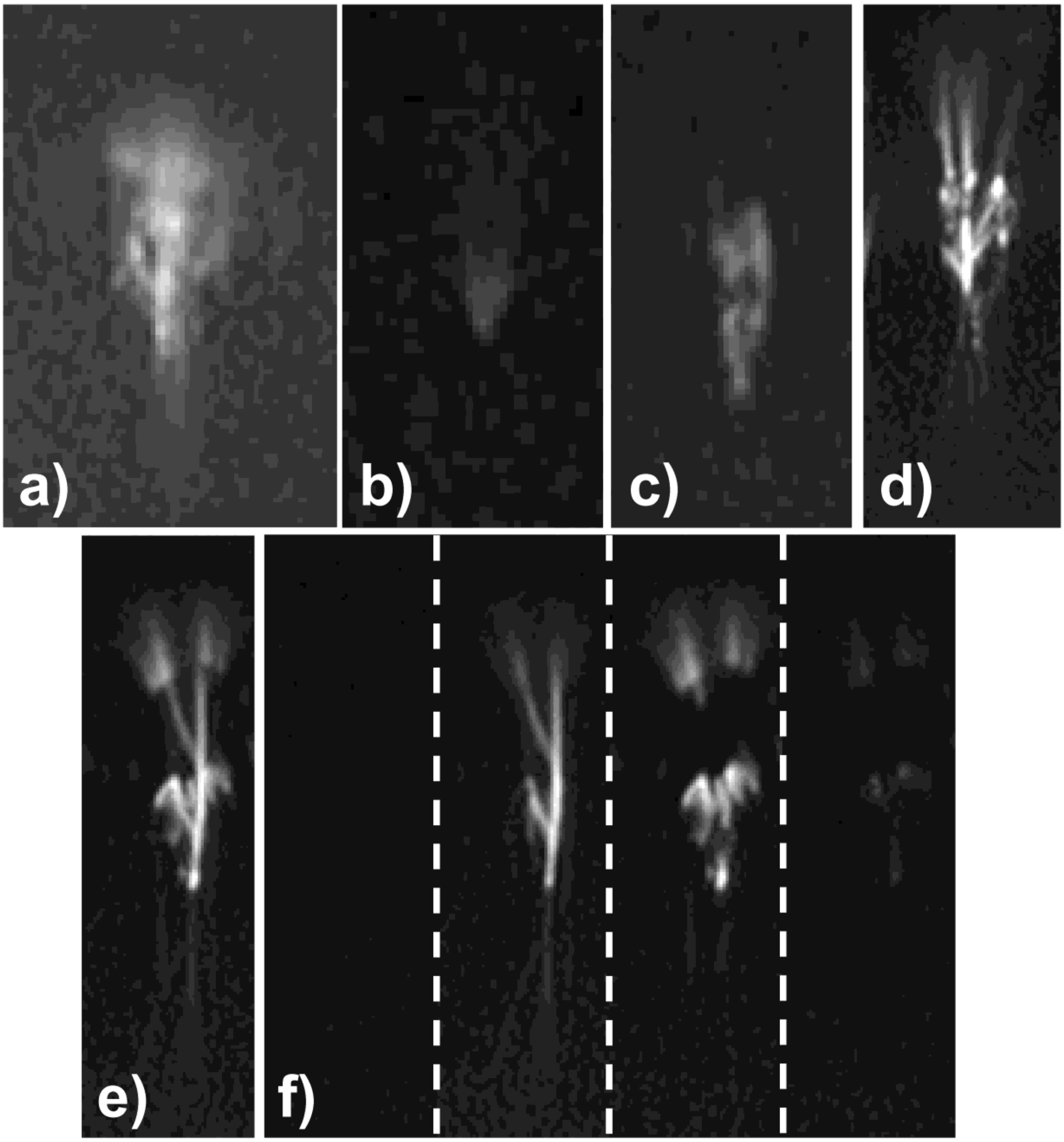


Figure 7. Sprites of peculiar shape observed in Central Europe. **a)** 01:28:33.902 UTC, 11. June, 2009.; **b)** 22:52:03.656 UTC, 07. Aug., 2008.; **c)** 22:37:15.511 UTC, 10. June, 2009.; **d)** a tree-carrot intermediate sprite form, 22:34:28.759 UTC, 02. Aug., 2009.; **e)** peak-hold image 21:28:06.862-882 UTC, 02. Aug., 2009.; **f)** consecutive video fields of the event on subplot e) by 20 ms. First video field corresponds to 21:28:06.842 UTC, 02. Aug., 2009.

Although setting up the shape categories was rather straightforward, sorting of the events was uneasy in several cases, because intermediate emission shapes have been observed. One characteristic example for such an intermediate form is shown on Figure 7d. These intermediate emission shapes can bear characteristic properties of more (mostly two) basic forms (Myokei et al., 2009). Unambiguous wishbones (i.e. a column with a very short and faint side branch), tree/carrot and angel/carrot hybrids have been encountered during the analysis of the Central European record set.

4.2. Classification by the number and configuration of sprite elements in an event

Considering the number of entities, the events have been divided into two groups: events of a single sprite entity (single sprites) and events consisting of two or more sprite entities (sprite clusters). Among sprite clusters, events containing sprite elements of only the same morphological class (homogeneous clusters) and events featuring sprites from more morphological classes (mixed clusters) have been distinguished.

In case of sprite clusters with three or more elements, also the configuration of the elements can be examined. Setting up the following categories is suggested in this aspect: line configuration (straight and non-straight lines), two-dimensional figure (including circularly symmetric configuration or that with bias), and random or non-symmetric configuration. While a special in-line configuration can be determined for events with only three sprite elements, a cluster needs to contain at least four sprite elements in order to be possibly sorted into one of the other sets. In events having only three sprite elements, the location of the parent lightning flash can be used as a point of reference. In case of circular or biased circular arrangement of the members of a cluster, a further distinction can be made according to the presence or absence of any elements in the center of the configuration.

Note that having images of a sprite cluster only from a single observation site severely limits the possibilities of making a proper configuration analysis. In order to determine the arrangement of the sprite elements from a single-site detection, the event must occur relatively close to the observation site so that it is photographed rather from below. Sprite elements of the cluster need to be well distinguishable and even in such a case an assumption must be made about the height range occupied by the emissions (Vadislavsky et al., 2009). For a more accurate analysis, the position of the sprite elements need to be determined from independent measurements, e.g. by triangulation from more optical records (Sentman et al., 1995; Lyons, 1996; Wescott et al., 2001; Sao-Sabbas et al., 2003; Stenbaek-Nielsen et al., 2010; Gamerota et al., 2011).

This study is based on sprite observations from a single optical detection site. Additionally, the majority of the analyzed events occurred relatively far from the recording site, so it was not possible to investigate the occurrence rates of the different sprite configurations using this data set only. Nevertheless, categories to classify sprites by the configuration of the appearing elements are suggested here for possible consideration in further research.

Note that Central European sprite detections discussed in this study support the observation that subsequent sprite events sometimes occur at or very near to the location of a previous sprite event (Haldoupis et al., 2010; Pasko et al., 2012). In 23 events, re-brightening of the longest lasting parts of sprites in a preceding event was observed, occasionally parrallel with an upcoming separate sprite event. This indicates that effects of a sprite event on the local medium persist much longer than the optical emission. In the following sections, two special types of sprite clusters are pointed out.

4.2.1. Special sprite clusters: jellyfish sprites

Jellyfish type sprites are unquestionably the brightest sprite events. Such an event is characterized by a high number of bright sprite elements with simultaneously observable extensive and bright glow and unusually lengthy and bright, dense and highly branching tendril structure. The morphological type of the elements of jellyfish sprites is not easy to determine due to the heavy overlap of individual entities and also because they mostly saturate the image (Figure 8, Figure 3f). For the same reason, it cannot always be determined if these clusters are homogeneous or they are of mixed type (Figure 8e). Nevertheless, many jellyfish sprites seem to be morphologically homogeneous. These events seem to consist solely of columniform sprites (Figure 8cd). According to this experience, some of the jellyfish type sprites reported by Williams et al. (2001) can be such clusters of bright column sprites (Figure 2ef, Figure 8acd). There are cases where some or more of the elements in the cluster are rather wishbone or tree sprites (Figure 8ab, Figure 3f). The upward branches here use to connect to the bottom of the central column and there can be more of them. The branches of such jellyfish sprites are, however, not very long i.e. they do not seem to reach higher than the half of the central column. A smaller fraction of jellyfishes (3 from all 29 events classified as jellyfish), on the other hand, probably has a very dense, tangled network of bright streamers and beads in their body, too. Although the network of streamers is generally not resolved in conventional frame rate video images, the wider, carrot-like shape of these sprites suggests this scenario (Figure 8e).

The name "jellyfish" was introduced by Pasko et al. (2000), nevertheless Gerken et al. (2000) and also Lyons (1996) have reported previously on sprites with well developed tendril structure, which can be equivalent to this type of sprite. Additionally, the description given by Stanley et al. (1999) for the well-developed angel sprites may also refer to this kind of event.

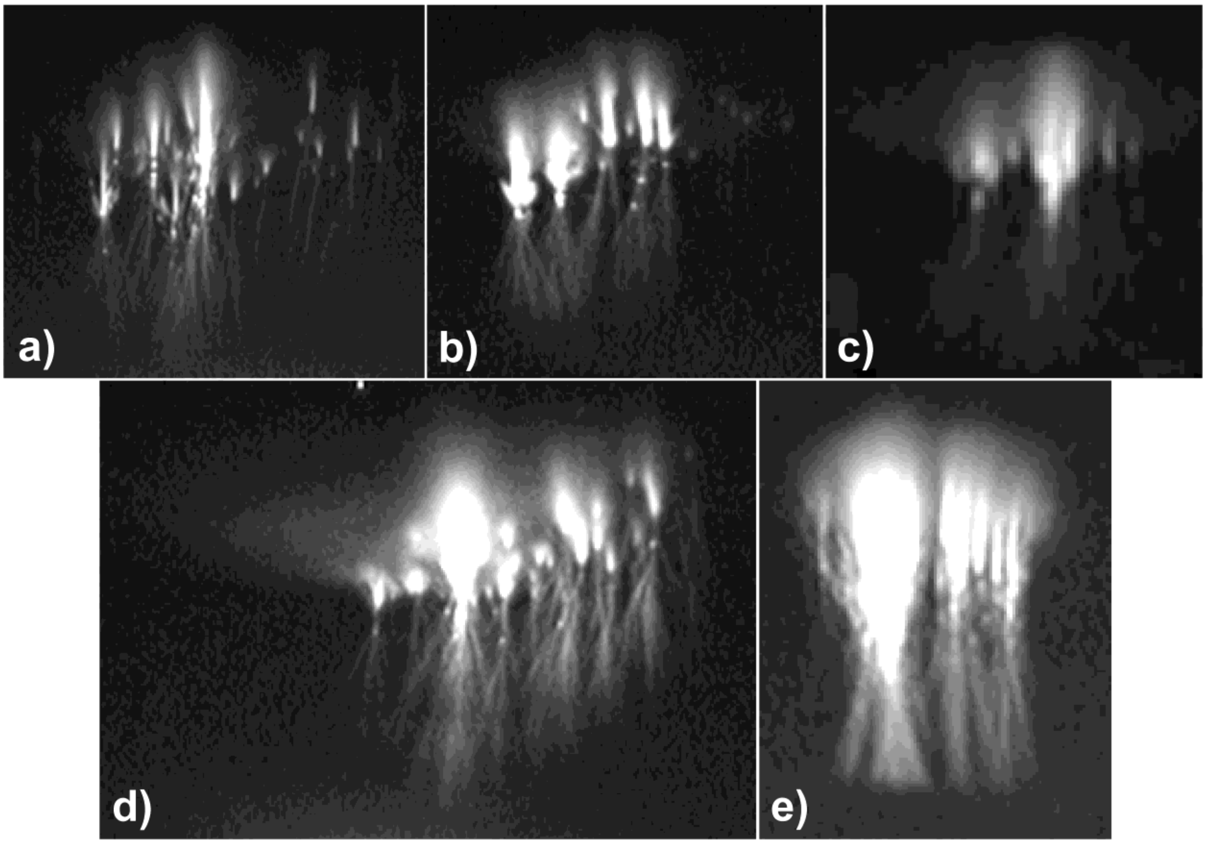


Figure 8. Jellyfish sprites observed in Central Europe. **a)** 20:17:41.769 UTC, 02. Aug., 2009. Tendrils of sprite elements on the right are bent as they follow the prevailing direction of electric field lines; **b)** 21:44:37.578 UTC, 07. Aug., 2008.; **c)** 01:01:14.829 UTC, 31. July, 2007.; **d)** 21:23:30.860 UTC, 07. Aug., 2008. Tendrils of sprite elements tend to bend toward the region in the thundercloud below the center of the sprite halo; **e)** 23:23:18.250 UTC, 10. June., 2009.

4.2.2. Special sprite clusters: dancing sprites

The other special sprite type is the so called "dancing" sprite (Figure 9). Basic characteristics of dancing sprites were given in the introduction. Note that dancing sprites may violate the "one parent lightning per event" assumption probably the most. As it was suggested earlier by Hardman et al. (2000), separate lightning strokes or even flashes may be associated with each sprite elements appearing in the virtual movement-chain of the sprite dance. This was not yet verified for dancing sprites observed in Central Europe. On one hand, single sprite producing +CG discharges can be associated with high in-cloud lightning activity (van der Velde et al., 2006) which may range over several tens of kms as in “spider” lightning events (Stanley, 2000; Lyons et al., 2006). This makes the region of enhanced electric field extend horizontally so that more sprites can be possibly produced in this extended region. On the other hand, cases have been found where more sprite producing +CG strokes were parts of one large lightning flash (Lang et al. 2010, 2011). In any case, considering all of a dancing sprite scene as one event may not be a big mistake, since the close temporal succession of sprite appearances and that the type of the appearing sprites is similar (or in fact the same) suggest that a connection exists between these emissions. Keeping this in mind, sprite elements separated by at most one video field showing no new sprites were still taken as one event if those sprites fitted into the visually recognized virtual movement-chain of the sprite dance. Such situation occurred in one third of the events which were classified as dancers.

Note that even the elements of a common sprite cluster do not necessarily appear all at the same time. Also with normal frame rate cameras, it was observed in 149 events (30% of all analyzed events) that new sprite elements showed up on the next video field following the first with recognizable sprite(s). Such events were not classified as a dancing sprite unless the appearance of new elements continued on at least one further consecutive video field. For dancing events, the virtual motion usually had one well recognizable direction, although the trajectory of this movement was sometimes obviously curved (Figure 9bc). Later appearing members of non-dancing clusters can appear asymmetrically next to earlier sprites as if the sprite started dancing. On the other hand, those new elements can also rather surround the older ones as a generic extension of the event. Having looked through the events with this in mind, there were no two directional (or multi directional) dancing sprites observed in the database. Note that the impression of movement is facilitated not only by the appearance of new sprite elements, but also by the spatially advancing phase of brightening of the already present elements of the cluster (Figure 9b). Brightening of any glows present in the event fitted in the virtual movement, too. Hardman et al. (2000) noted that the sprite element which occurred at the end of the virtual movement of dancing sprites was occasionally different from those appeared earlier. This last element called the “terminating sprite” was usually larger and/or brighter than the others in the event. This phenomenon was observed in the analyzed Central European dataset, too (Figure 9ac).

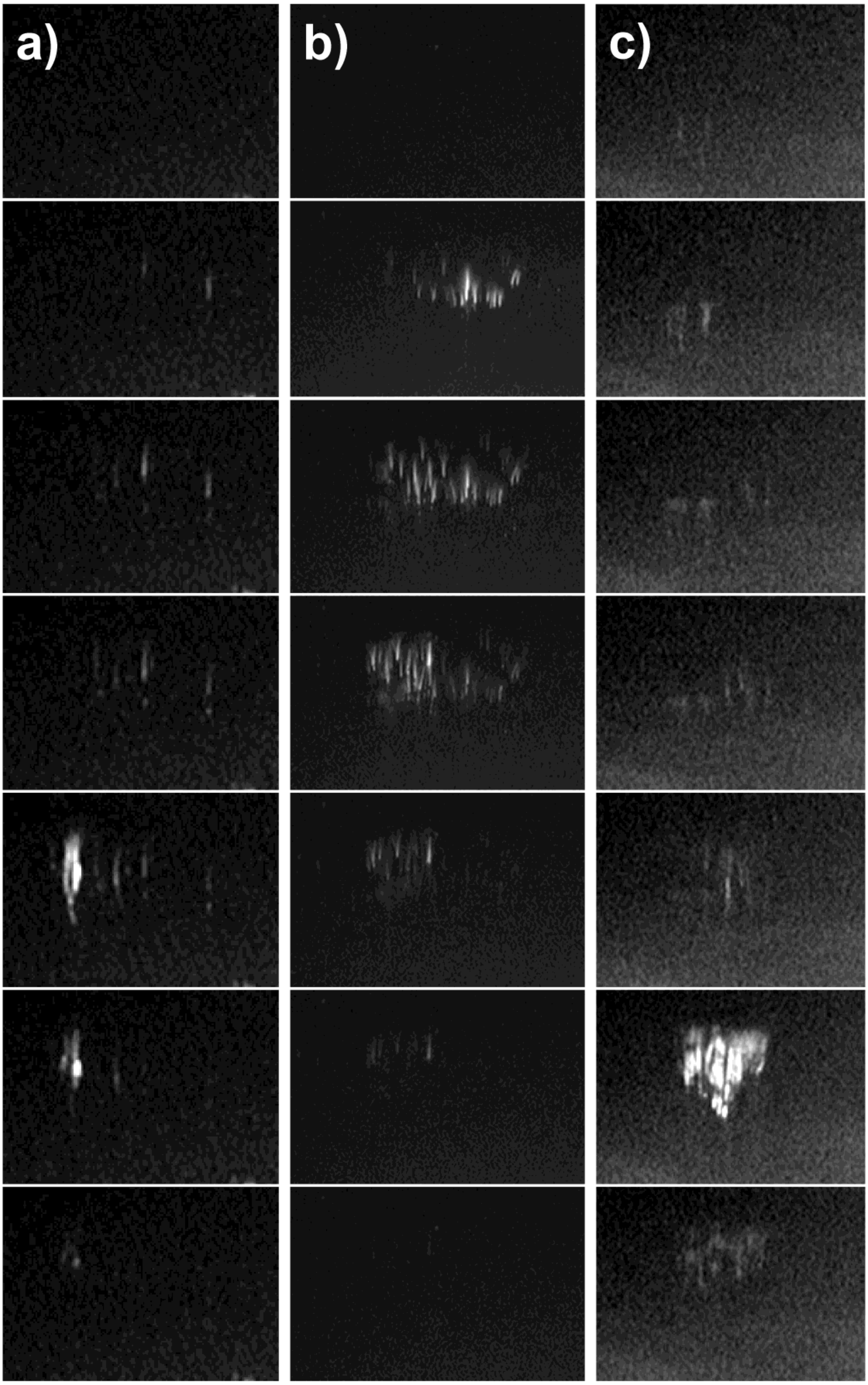
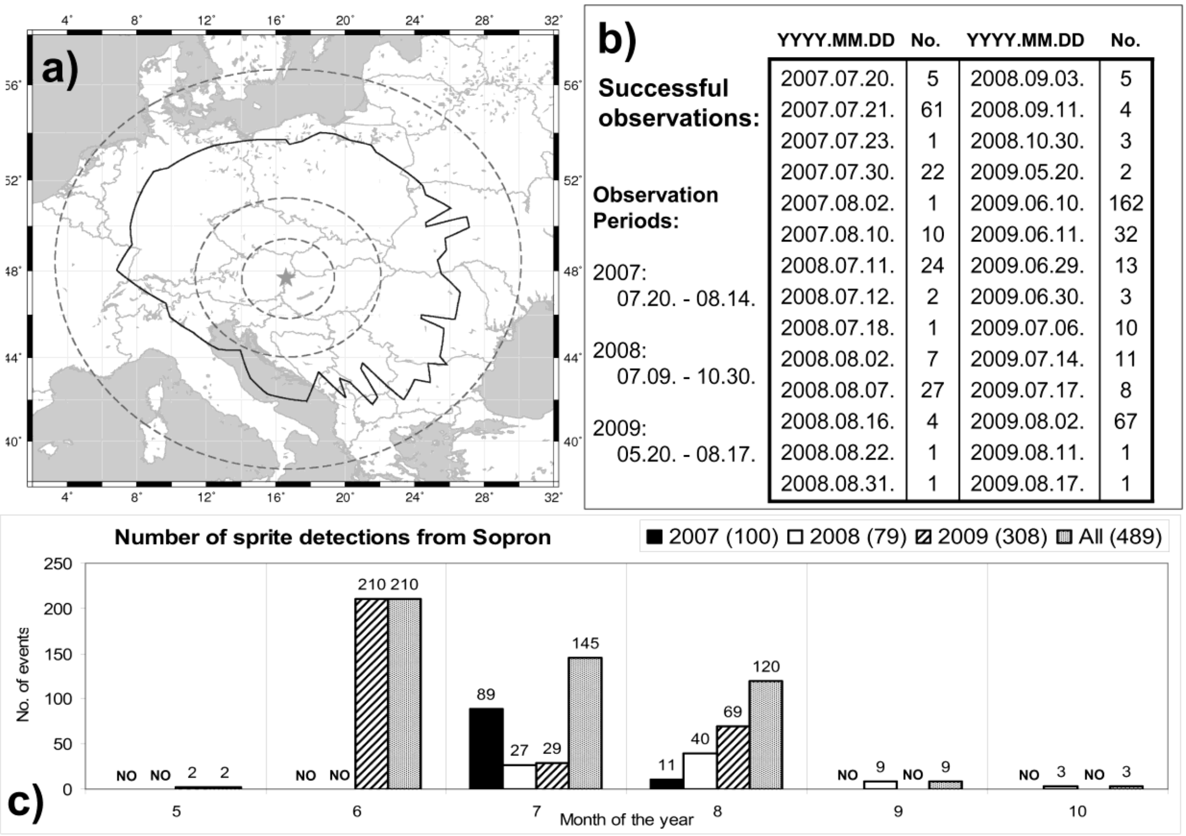


Figure 9. Dancing sprites observed in Central Europe. Consecutive video fields are by 20 ms. **a)** first field is at 23:09:25.556 UTC, 30. July, 2007.; **b)** first field is at 22:37:37.464 UTC, 02. Aug., 2009.; **c)** first field is at 21:59:59.188 UTC, 10. June, 2009.

5. Statistics of occurrences

Only a subset of all sprite events occurred inside the viewing range of the camera in Sopron (Figure 10a) has been observed during the three years covered in this report (Figure 10b). Unfavorable viewing conditions, system maintenance periods, unavailability of an observer as well as the finite field of view and sensitivity of the camera limited the number of detected sprites. The number of observed sprites per month, however, clearly reinforces the general experience that the thunderstorm season lasts practically from late May to early September in Central Europe (Figure 10c).



YYYY.MM.DD	No.	YYYY.MM.DD	No.
2007.07.20.	5	2008.09.03.	5
2007.07.21.	61	2008.09.11.	4
2007.07.23.	1	2008.10.30.	3
2007.07.30.	22	2009.05.20.	2
2007.08.02.	1	2009.06.10.	162
2007.08.10.	10	2009.06.11.	32
2008.07.11.	24	2009.06.29.	13
2008.07.12.	2	2009.06.30.	3
2008.07.18.	1	2009.07.06.	10
2008.08.02.	7	2009.07.14.	11
2008.08.07.	27	2009.07.17.	8
2008.08.16.	4	2009.08.02.	67
2008.08.22.	1	2009.08.11.	1
2008.08.31.	1	2009.08.17.	1

Figure 10. Sprite detections from Sopron, Hungary in 2007-2009. **a)** Solid line marks the border of the area in Central Europe above which the 50-90 km height range is fully observable from the detection site (star). Dashed lines indicate 200 km, 400 km, 1000 km ranges from Sopron. **b)** Observation periods, dates of successful observations as well as the corresponding numbers of detected events. **c)** Monthly distribution of detected events. “NO” means no observation in the corresponding year.

The number of sprite events observed above a storm was rather varying (Figure 10b). In most of the cases the number of detected events was below 30 per storm. While in more cases only a singe sprite event was recorded, the number of captured events was more than 60 on three nights. During an exceptional storm on the night of 10th June, 2009 as many as 162 sprite events were captured.

5.1. Statistics of types and cardinality

The grand majority of observed sprites occurred in clusters rather than alone (Figure 11). More than half of sprite clusters were of mixed type, while only about one third of the clusters contained unambiguously only one morphological sprite type.

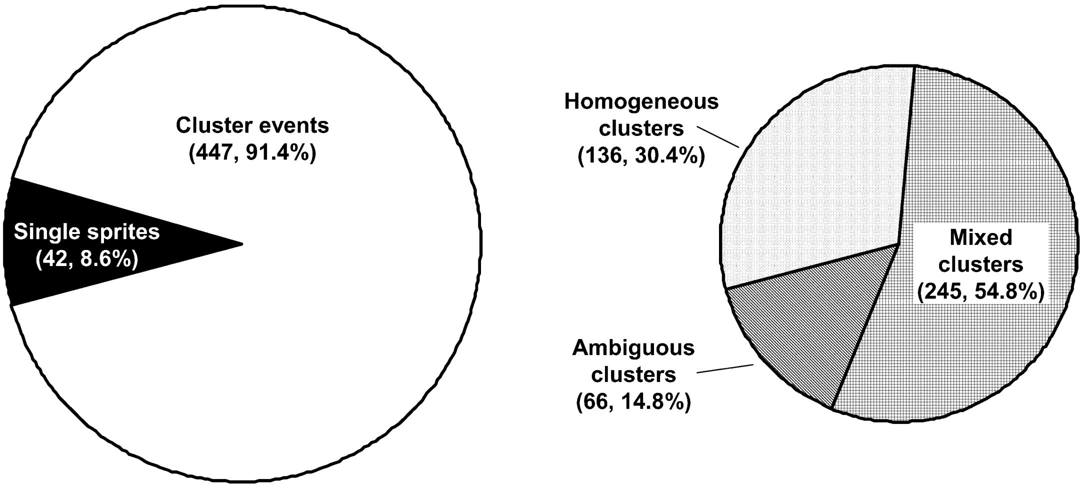
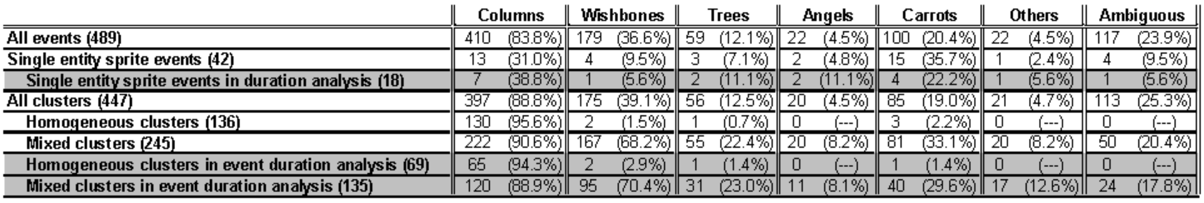


Figure 11. Distribution of the observed occurrences of sprite types in Central Europe in 2007-2009 by the cardinality of events.

Comparing the occurrence rates of sprites in Central Europe to the statistics found by Su et al. (2002a) for land sprites observed around Taiwan, the dominance of cluster sprite events over single emissions is apparent in both datasets (91.4 % and 64 % in Central Europe and in Asia, respectively). The ratio of the numbers of the observed single and cluster events, however, was found to be much lower in the present study (Figure 11). The low percentage of columniform sprites (21 %), the high percentage of carrot sprites (55 %), and the lower fraction of mixed events (14 %) among the events detected by Su et al. (2002a) compared to the Central European observations from Sopron suggest that system sensitivity and/or event detection criteria were probably different in these Asian observations. This can explain why the generally very bright carrots have been detected in greater number, and that less bright columns occurring fairly frequently also in mixed events were reported less often. Differences in the ratios of detected occurrences in the two regions point out the importance of considering the finite detection sensitivity of the equipment at the interpretation of the statistics of the observations.

In Central Europe, columniform type sprites were observed the most frequently in general (Table 1). This finding for these continental observations suggests that the abundance of this sprite form is a general characteristics of sprite events, since column sprite have been observed the most frequently also above winter thunderstorms, i.e. over the Sea of Japan and the eastern Mediterranean Sea (Takahashi et al., 2003; Hayakawa et al., 2004; Adachi et al. ,2005; Ganot et al., 2007; Yair et al., 2009; Suzuki et al., 2011). Only among single sprite events, two more carrots (15) were found than columns (13), which means that the occurrence rate for these types in this category is practically equal. On the other hand, angel sprites seem to be the rarest morphological type.

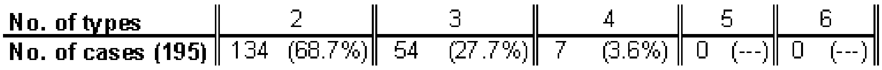
Table 1. Occurrences and occurrence rates of various morphological types among the detected sprite events in Central Europe in 2007-2009.



	Columns		Wishbones		Trees		Angels		Carrots		Others		Ambiguous	
All events (489)	410	(83.8%)	179	(36.6%)	59	(12.1%)	22	(4.5%)	100	(20.4%)	22	(4.5%)	117	(23.9%)
Single entity sprite events (42)	13	(31.0%)	4	(9.5%)	3	(7.1%)	2	(4.8%)	15	(35.7%)	1	(2.4%)	4	(9.5%)
Single entity sprite events in duration analysis (18)	7	(38.8%)	1	(5.6%)	2	(11.1%)	2	(11.1%)	4	(22.2%)	1	(5.6%)	1	(5.6%)
All clusters (447)	397	(88.8%)	175	(39.1%)	56	(12.5%)	20	(4.5%)	85	(19.0%)	21	(4.7%)	113	(25.3%)
Homogeneous clusters (136)	130	(95.6%)	2	(1.5%)	1	(0.7%)	0	(---)	3	(2.2%)	0	(---)	0	(---)
Mixed clusters (245)	222	(90.6%)	167	(68.2%)	55	(22.4%)	20	(8.2%)	81	(33.1%)	20	(8.2%)	50	(20.4%)
Homogeneous clusters in event duration analysis (69)	65	(94.3%)	2	(2.9%)	1	(1.4%)	0	(---)	1	(1.4%)	0	(---)	0	(---)
Mixed clusters in event duration analysis (135)	120	(88.9%)	95	(70.4%)	31	(23.0%)	11	(8.1%)	40	(29.6%)	17	(12.6%)	24	(17.8%)

The appearance of many different sprite types is not very much characteristic in mixed sprite clusters. Most mixed clusters featured just two types (Table 2).

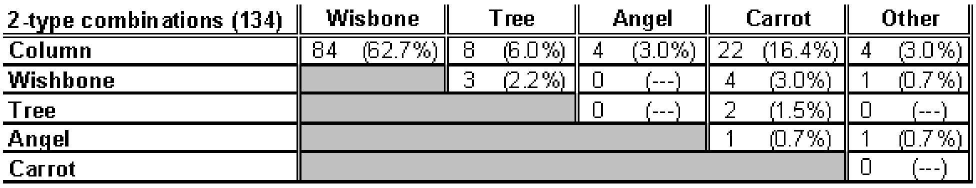
Table 2. Number of appearing morphological types in mixed sprite clusters containing no ambiguous type elements.



No. of types	2		3		4		5		6	
No. of cases (195)	134	(68.7%)	54	(27.7%)	7	(3.6%)	0	(---)	0	(---)

Column sprites were almost always part of the cast and they appeared most frequently with wishbone or carrot sprites in two-type events (Table 3).

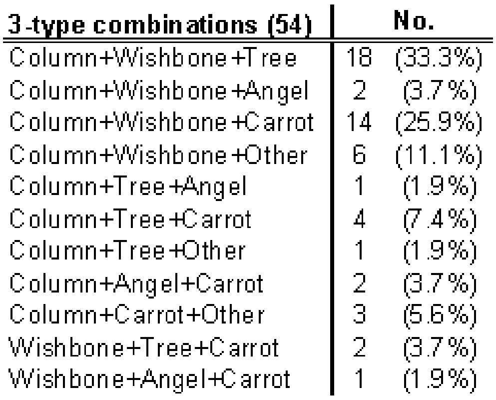
Table 3. Number and occurrence rate of mixed sprite clusters containing exactly two morphological types of sprites. (Events with ambiguous type elements have not been counted).



2-type combinations (134)	Wisbone	Tree	Angel	Carrot	Other
Column	84 (62.7%)	8 (6.0%)	4 (3.0%)	22 (16.4%)	4 (3.0%)
Wishbone		3 (2.2%)	0 (---)	4 (3.0%)	1 (0.7%)
Tree			0 (---)	2 (1.5%)	0 (---)
Angel				1 (0.7%)	1 (0.7%)
Carrot					0 (---)

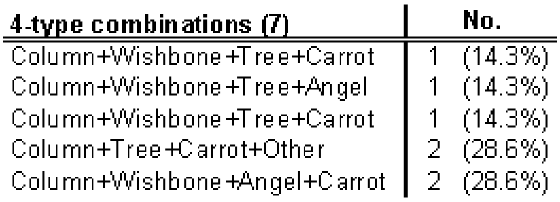
In three-type events (Table 4), the column-wishbone-tree trio was observed the most often, closely followed by the number of the column-wishbone-carrot sets. Although many other type combinations were also observed, these were much less frequent (Tables 2 to 5). Among them, angel sprites showed less affinity to appear with other morphological types.

Table 4. Number and occurrence rate of mixed sprite clusters containing exactly three morphological types of sprites. (Events with ambiguous type elements have not been counted).



3-type combinations (54)	No.	
Column+Wishbone+Tree	18	(33.3%)
Column+Wishbone+Angel	2	(3.7%)
Column+Wishbone+Carrot	14	(25.9%)
Column+Wishbone+Other	6	(11.1%)
Column+Tree+Angel	1	(1.9%)
Column+Tree+Carrot	4	(7.4%)
Column+Tree+Other	1	(1.9%)
Column+Angel+Carrot	2	(3.7%)
Column+Carrot+Other	3	(5.6%)
Wishbone+Tree+Carrot	2	(3.7%)
Wishbone+Angel+Carrot	1	(1.9%)

Table 5. Number and occurrence rate of mixed sprite clusters containing exactly four morphological types of sprites. (Events with ambiguous type elements have not been counted).



4-type combinations (7)	No.	
Column+Wishbone+Tree+Carrot	1	(14.3%)
Column+Wishbone+Tree+Angel	1	(14.3%)
Column+Wishbone+Tree+Carrot	1	(14.3%)
Column+Tree+Carrot+Other	2	(28.6%)
Column+Wishbone+Angel+Carrot	2	(28.6%)

The total number of sprite entities in an event was not possible to count unambiguously in 36% of the analyzed events because of the overlap of sprite elements in a cluster, and/or due to the saturation or blur in the image. Therefore, the presented numbers should be taken as a close lower bound for the real number of elements in an event (Figure 12). Note that dancing sprites were not included in this statistics. The number of cases decays as the number of observed entities in an event grows and the number of single sprites fits well at the beginning of this distribution (Figure 12a). The number of column sprites tends to dominate in the majority of events. For example 3 to 10 times more columns were counted in 68% of two-type sprite events than the number of not column sprites. The highest number of column sprites counted in a cluster was 37 (this was a homogeneous cluster). The number of each of the other-than-column sprite forms, on the other hand, basically remained below 4 in homogeneous events (Figure 12b) and below 6 in mixed events (Figure 12c). Only in one case, 5 carrot sprites were observed in a homogeneous cluster (Figure 6l), and in two cases 7 and 9 wishbones were counted in mixed clusters.

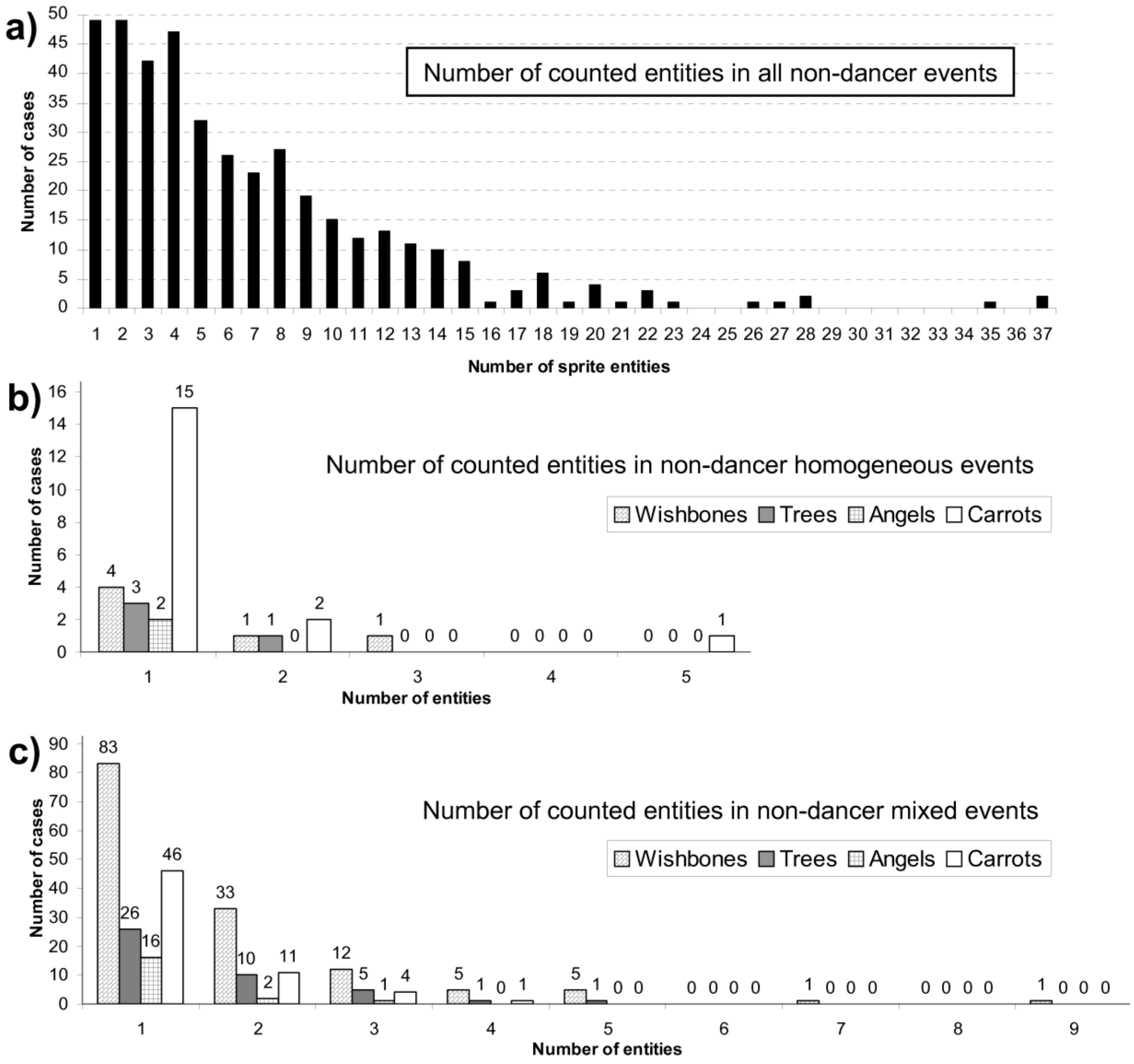
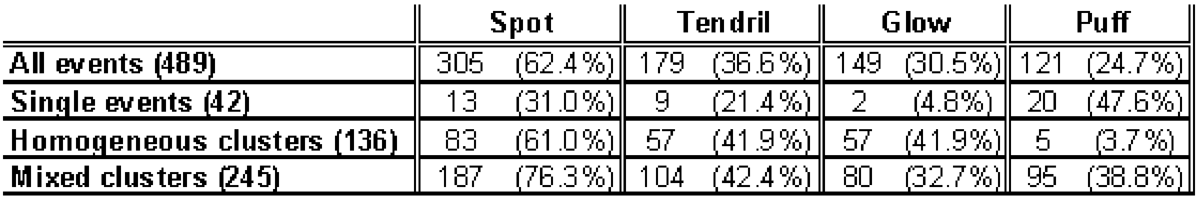


Figure 12. Number of sprite elements in the observed events. Note that the set of homogeneous events contains single sprites, too. The given number of elements is a lower bound for the real number of elements in an event.

5.2. Statistics of sprite features

In the following statistics, the presence of a sprite feature is considered, i.e. if the actual feature could or could not be observed with at least one sprite element in an event. This does not mean that all elements in a cluster bore that feature. In fact it was observed very rarely that all members of a cluster showed the same set of features. Among the occasionally observable sprite features, the occurrence of spots was the most frequent (Table 6). In most of the cases, a single spot could be assigned to a sprite element. This happened even in cases where the sprite was very bright (Figure 4a, Figure 5bc, Figure 6a). Spots were usually of similar brightness as the sprite body, so this structure often resembles an exclamation mark in cases of column sprites (Figure 2b). Two or more spots below a single entity were counted in 104 events. More records show a cluster of sprites together with many spots, but in those cases it was not always possible to determine the spot-element correspondence (e.g. Figure 1b). Note that elongated spots were observed the most frequently with column sprites, i.e. in 57 of all 227 events containing columns with spots.

Table 6. Occurrences and occurrence rates of different sprite features.



	Spot	Tendril	Glow	Puff
All events (489)	305 (62.4%)	179 (36.6%)	149 (30.5%)	121 (24.7%)
Single events (42)	13 (31.0%)	9 (21.4%)	2 (4.8%)	20 (47.6%)
Homogeneous clusters (136)	83 (61.0%)	57 (41.9%)	57 (41.9%)	5 (3.7%)
Mixed clusters (245)	187 (76.3%)	104 (42.4%)	80 (32.7%)	95 (38.8%)

Only unambiguous observations of other beads either along the sprite tendrils or in the sprite body have been noted because of the limited image resolution and/or saturation issues discussed earlier. Due to these reasons, only quasi-qualitative survey of bead occurrences could be done, hence the corresponding statistics are not included in Table 6. The presence of beads could be clearly identified in the body of more than half of the analyzed carrot sprites and angel sprites. Note that beading was more easily traced in less structured sprite bodies. With the decreasing complexity of the sprite form, however, the occurrence rate of beads in the sprite body tend to decrease. Among tree sprites, beads in the body have been seen in 17 of 59 events (28.8%) and the detection rate is only about 6% for wishbones and less than 3% in columns. Note that column and wishbone sprites the bodies of which have been divided into more bright parts by more dark bands (Figure 3bd) were counted in the latter two categories.

Beads in the sprite tendril region have been unambiguously detected only when sprite tendrils were observable, too. Generally tendrils were the next most frequently observed sprite feature after spots; except for single sprites, where puffs dominated the occurrence rate even over spots (Table 6). The detection rate of beads in the tendril region was 14-18% among column, wishbone, and tree sprites with visible tendrils, while among angel and carrot sprites of such, it jumped above 30%.

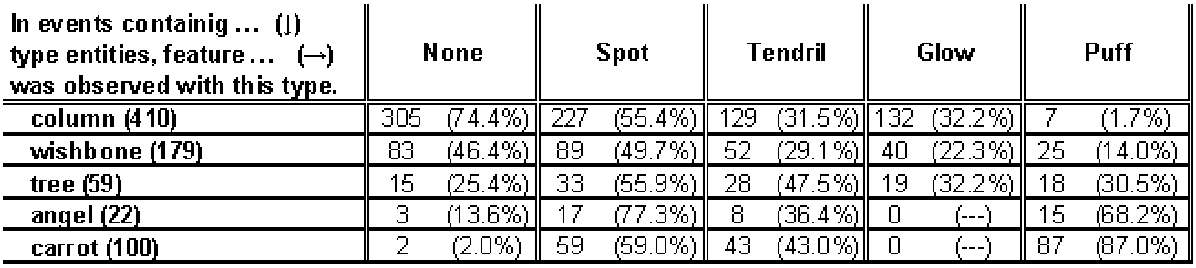
In contrast to puffs, the relative occurrence rate for glows was the lowest among single sprite events. Compared to singles, the ratio of the occurrences for puffs and glows is reversed in homogeneous clusters. This suggests that the body of singly appearing sprite entities tend to be below the region of transition zone (Pasko et al., 1998), while the top of sprite elements in homogeneous clusters reach up into this region.

The majority of glows observed in the analyzed record set were bulb-like corresponding to the transition zone in sprite emissions. Glows without unambiguous bulb-like distribution around sprite entities (Figure 1c) were noted in 36 events. Small separation between sprite elements, however, prohibited the unambiguous distinction of these glows from those corresponding clearly to the transition zone (Figure 1ab). Unambiguous striation in glows has not been recognized in the examined record set. Vertical pattern in the brightness of sprite bodies surrounded by glows, however, was found to be present in 13 cases (Figure 1c). Note that coherency among the brightness patterns occurred in various elements of a sprite cluster could not be observed unambiguously. While explicit upward propagation of glows could be observed in only 6 events from the considered record set of Central European observations, upward extension of the glowing region without noticeable actual movement has also been detected in additional cases.

Taking the statistics for different morphological classes separately, the spot-tendril-glow-puff ranking with the decreasing occurrence rates is valid for columns and for wishbone and tree sprites (Table 7). With angel sprites, no glow emissions were observed unambiguously and for carrot sprites the presence of this feature could not be clearly determined due to the high density of bright streamers which usually saturated the image of the sprite body. Occurrences of puffs tend to be more frequent in angel sprites, and this feature becomes characteristically dominant among carrot sprites. This seems to indicate that the body of angel and carrot sprites tends to form within the streamer zone below the transition zone (Pasko et al., 1998). The most sprite elements without any feature were observed among column and wishbone sprites, while angel or carrot sprites of such were explicitly rare.

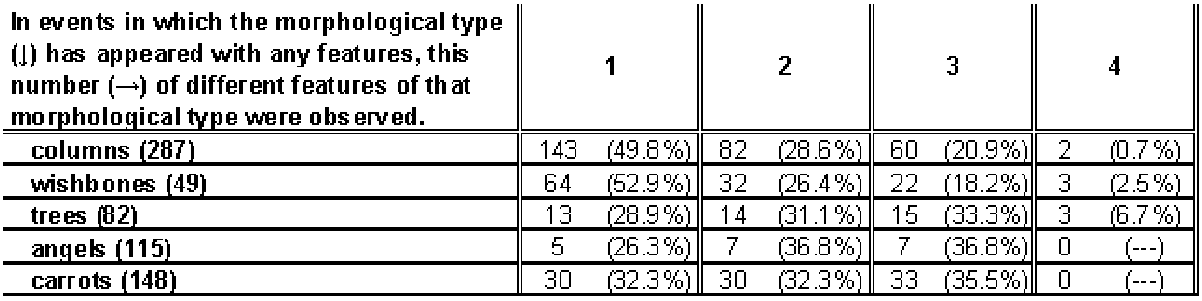
The number of simultaneously observable features (in an event, but not necessarily with the same sprite element) tends to be higher for angel and carrot sprites, while single feature columns and wishbones are about as frequent as columns and wishbones with more features (Table 8). It was found that tendrils and glows are often observable together in multi-feature events. This observation supports the similar finding by Jing et al. (2008). For columns, wishbones, and trees, these two features were observed simultaneously as many times as the sum of cases where only glows or only tendrils were present. Glows and puffs, on the other hand, practically do not appear in the same event. This suggests that the formation of these two sprite features happens under different electric conditions. These conditions are yet to be identified but it seems that and the required conditions for the formation for puffs are the most frequently realized with angel and carrot sprites.

Table 7. Occurrences and occurrence rates of different features observed with various morphological sprite types.



In events containig ... (↓) type entities, feature ... (→) was observed with this type.	None		Spot		Tendril		Glow		Puff	
column (410)	305	(74.4%)	227	(55.4%)	129	(31.5%)	132	(32.2%)	7	(1.7%)
wishbone (179)	83	(46.4%)	89	(49.7%)	52	(29.1%)	40	(22.3%)	25	(14.0%)
tree (59)	15	(25.4%)	33	(55.9%)	28	(47.5%)	19	(32.2%)	18	(30.5%)
angel (22)	3	(13.6%)	17	(77.3%)	8	(36.4%)	0	(---)	15	(68.2%)
carrot (100)	2	(2.0%)	59	(59.0%)	43	(43.0%)	0	(---)	87	(87.0%)

Table 8. Number of different features observed simultaneously with various morphological sprite types.

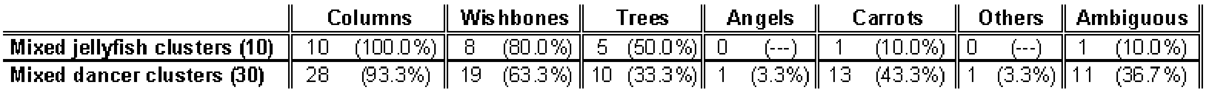


In events in which the morphological type (↓) has appeared with any features, this number (→) of different features of that morphological type were observed.	1		2		3		4	
columns (287)	143	(49.8%)	82	(28.6%)	60	(20.9%)	2	(0.7%)
wishbones (49)	64	(52.9%)	32	(26.4%)	22	(18.2%)	3	(2.5%)
trees (82)	13	(28.9%)	14	(31.1%)	15	(33.3%)	3	(6.7%)
angels (115)	5	(26.3%)	7	(36.8%)	7	(36.8%)	0	(---)
carrots (148)	30	(32.3%)	30	(32.3%)	33	(35.5%)	0	(---)

5.3. Statistics of jellyfish and dancing sprites

It is the characteristic combination of sprite features (simultaneously appearing bright glows and tendrils) according to which jellyfish sprites has been defined as a special subset of sprite clusters in this paper. Only 6.5% (29/447) of the observed sprite clusters were sorted in this category. Note that only 7 jellyfish events were preceded or observed together with a halo. The majority of jellyfish sprites were found to be homogeneous clusters of columniform elements (18 events). Columns were part of all mixed jellyfish events, too. Besides columns, wishbones and tree sprites could be observed in these clusters. A carrot type sprite was counted only once (Figure 8e) and no angel sprite was recognized among the observed jellyfish events (Table 9). According to the experience, jellyfish type events do not contain many sprite types; two different forms were counted in 6 cases (21%), 3 different forms (the most) were observed only in 3 cases (10%).

Table 9. Morphological type occurrences in mixed jellyfish and dancing sprites



	Columns	Wishbones	Trees	Angels	Carrots	Others	Ambiguous
Mixed jellyfish clusters (10)	10 (100.0%)	8 (80.0%)	5 (50.0%)	0 (---)	1 (10.0%)	0 (---)	1 (10.0%)
Mixed dancer clusters (30)	28 (93.3%)	19 (63.3%)	10 (33.3%)	1 (3.3%)	13 (43.3%)	1 (3.3%)	11 (36.7%)

Dancing sprites form another special group of sprite clusters, since these events can possibly consist of more "conventional" events which seem to be connected to each other. According to the applied definition, 9% (44/489) of all observed sprite events could be sorted in this category. Mixed events dominate among dancing sprites 68% (30/44), while only 14% (6/44) of dancer events was unambiguously homogeneous. The morphological type of all elements in the remaining 18% (8/44) could not be clearly resolved. All homogeneous dancing sprite clusters consisted of columniform sprites. This type was present and predominant also in the vast majority of mixed dancing clusters (Table 9). The composition of types in dancing sprites mirrors the general trends in mixed sprite clusters, but here angel sprites have a smaller, while carrot sprite have a larger occurrence rate. More different sprite types tend to appear in dancing sprite events slightly more frequently than in jellyfish sprites. At least two sprite types were observed in 45% of dancing events (20/44) and at least three kinds of sprites were counted in 8 cases (18%). Larger and brighter terminating sprites (most frequently carrot sprites) in dancing events have been observed in 10 cases. Note that in 4 additional cases a larger and brighter sprite element appeared in the middle of a dancing sprite sequence, while in other events the brightest sprites occurred in the beginning of the sequence.

Among sprite features, spots have been observed the most frequently, i.e. in roughly half of the dancing sprite events. Bright sprites among the dancers used to show more features characteristic to their morphological class, whereas especially tendrils were practically unobservable with entities having a fainter body. In the "dance" of sprites, 2-6 new elements appeared during the exposure time of one video field (20 ms). The speed of the virtual movement was not constant; the separation of adjacent sprite entities varied considerably. The total number of elements in an event varied between 6 and 20.

5.4. Optical duration of sprite emissions

Because of non-constant viewing conditions, source-observer distances (observed event elevation angles), and camera settings, proper analysis of optical duration of sprite emissions could not be performed involving all of our detections in Central Europe. Camera settings, however, has not been changed very much, so if events either too close or too far from the observation site are excluded, a statistical approach of the detected event durations is expected to reflect valid trends. Following this idea, a subset of events appearing in the distance range of 200-400 km from Sopron (Figure 10a) has been chosen for the analysis of sprite duration. This subset happens to be fairly populous. It contains 306 events, 62.6% of all cases considered in this study. The set includes 18 single sprites, and 24 jellyfishes as well as 32 dancers among the sprite clusters, so the statistical analysis of these samples is meaningful. Note that the duration of an event is calculated in this study from the number of de-interlaced video frames on which any emission related to the considered event is visually perceptible. The time resolution is, therefore, 20 ms.

Note that the given duration characterizes the whole event and so it cannot be associated with individual element in sprite clusters. Since the first appearing element of a cluster is not necessarily the same as the last disappearing one and the duration of individual sprite entities has not been considered in this study, the optical lifetimes given here cannot be associated with the sprite entity of the longest emission in an event either.

5.4.1. Optical duration of sprite features

Although quantitative analysis of the optical durations of the occasionally observable sprite features has not been carried out in the framework of the present study, obvious trends in the durations of these features have been observed. The most durable emissions were those of the bright body of column and wishbone sprites and those of spots and beads especially inside the body of more developed forms (i.e. trees, angels, carrots). Note that despite of the lasting luminosity observed in columns, the emissions in streamer channels of trees, angels, and carrots do not seem to be of long lifetime. Streamer channels forming the body of such sprites as well as those channels connecting the body with puffs disappeared after the second video field (i.e. in 40 ms). Taking into account that video field separators intercepted the process of sprite formation in such cases, the actual lifetime of these channels is probably much shorter.

Among various beads, those along the sprite tendrils seem to have the shortest duration. When formed in trees, in angels, or in carrots, however, they are longer observable than the streamer channels in the sprite body. If these features appear, spots and beads inside the sprite body are found to be visible longer than beads along the tendrils. The optical lifetime of beads inside the body of tree, angel, and carrot sprites, on the other hand, was observed to exceed that of spots in the same sprite entity. Even if they appear one video field later, the duration of spots in columns and in wishbone sprites is more or less the same as the duration of the emission from the sprite body.

Sprite tendrils and bulb-like glows have never been observed longer than two video fields (40 ms) regardless of the morphological class of the sprite they were detected with. This must be viewed in the same context as the observed durations of streamer channels in tree, angel, and carrot sprites. Compared to these features, not bulb-like sprite glows have been occasionally observed for one or two video fields longer (+20-40 ms) so that the movement or upward extension of them could be recognized. Glow durations longer than 3 video fields (60 ms), however, have not been observed in the analyzed record set. The observed optical lifetime of puffs is in the same range as that of the not bulb-like glows.

5.4.2. Optical duration of jellyfish and dancing sprites

The duration of large and bright jellyfish sprites was compared to that of non-jellyfish events (Figure 13).

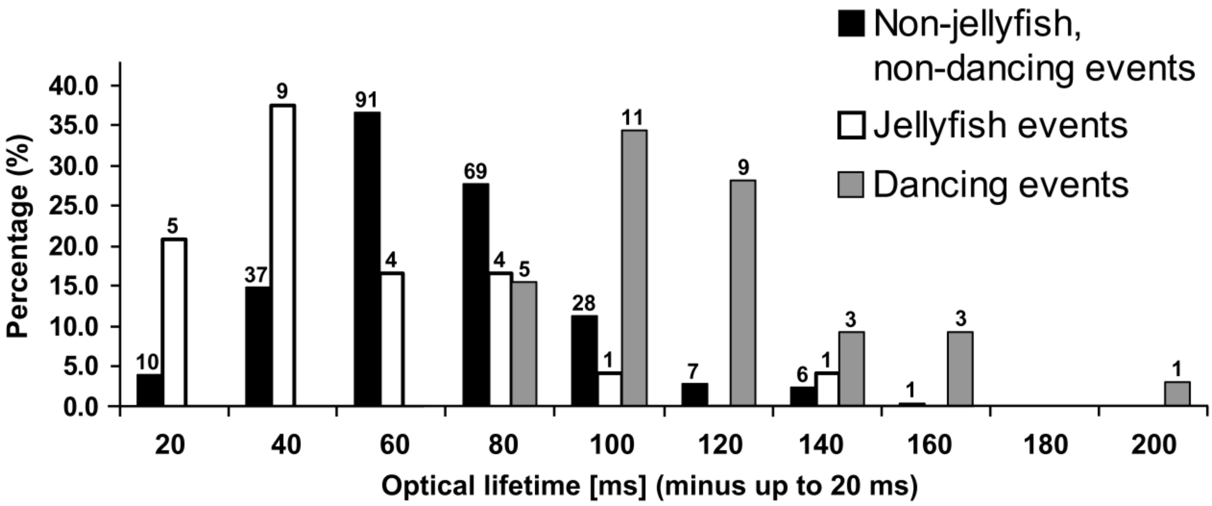


Figure 13. Distribution of event durations of selected events. On top of each bars, the numbers of the corresponding cases are plotted.

Dancing sprites were treated separately because of the different time-pattern of element appearances in them. In accordance with the notation of Winckler et al. (1996), it was found that jellyfish sprites indeed tend to have shorter lifetime. The apparent longer total duration of dancing sprites comes by no surprise and it reinforces the idea that these events possibly consist of more concatenated "regular" sprite events (Hardman et al. 2000). Because of this, dancing sprites were not involved further in the analysis of event durations.

5.4.3. Optical duration of the event and the number and type of appearing sprites

In order to find morphological properties which are possibly related to the duration of sprites, sprite event durations were plotted against the number of sprite elements counted in the events (Figure 14). Homogeneous events including single and cluster occurrences were distinguished from mixed sprite clusters and points corresponding to (also) jellyfish sprites were marked, too. It is apparent that the majority of events last for 40-80 ms. While long sprite durations (>80 ms) also occur with clusters having 15 or less elements, such long lasting luminosity was not observed in events counting more than 25 sprite elements.

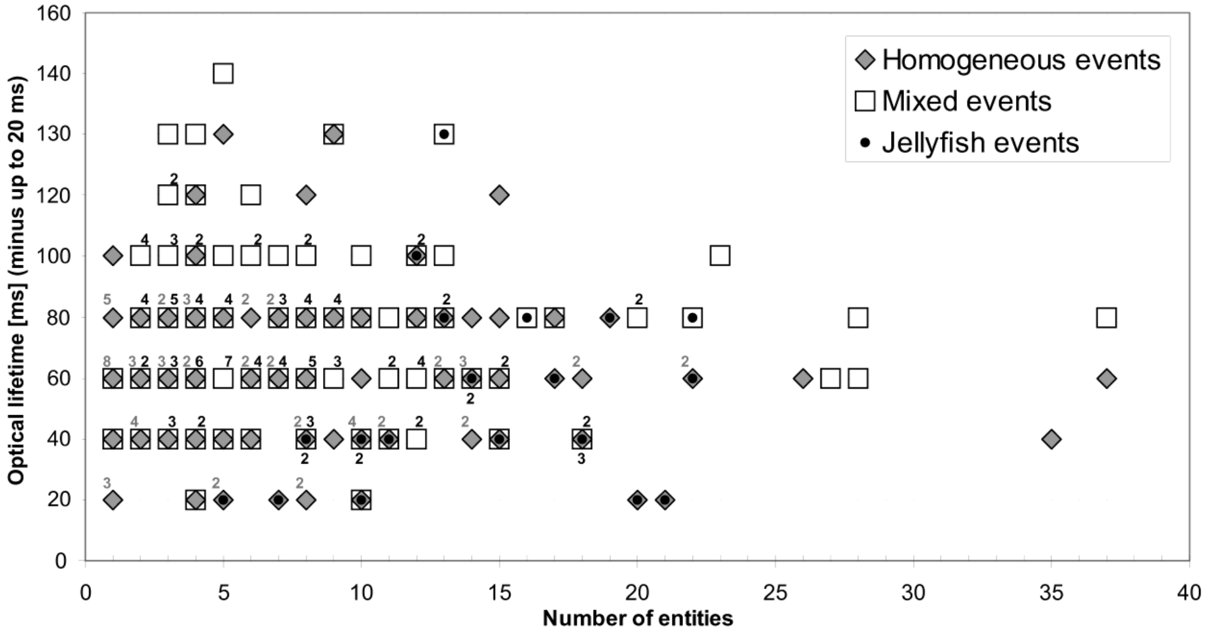


Figure 14. Event durations and the corresponding number of sprite elements. To up and left from each point, the multiplicity of the corresponding homogeneous events is written. To up and right from each point is the multiplicity of corresponding mixed events. Below each point is the multiplicity of corresponding jellyfishes. Only multiplicities greater than 1 are indicated.

The set of longer lasting events is dominated by mixed sprite clusters (also for clusters of many sprites). At the same time, there are only a few mixed events among the events of the shortest recorded duration of less than 20 ms (one video field). This tendency is also reflected in the average duration of homogeneous and mixed events (60.2 ms and 72.8 ms, i.e. 3.01 and 3.64 video fields, respectively). Although jellyfish sprites are not the most populous sprite clusters, they have a relatively high number of elements. Despite of this, this subclass does not separate from other events in the number-of-elements – event-duration plane. The distribution of jellyfish sprites rather follows the trend of homogeneous events. Therefore, homogeneous events (including single and cluster occurrences) and mixed sprite clusters are analyzed separately in what follows.

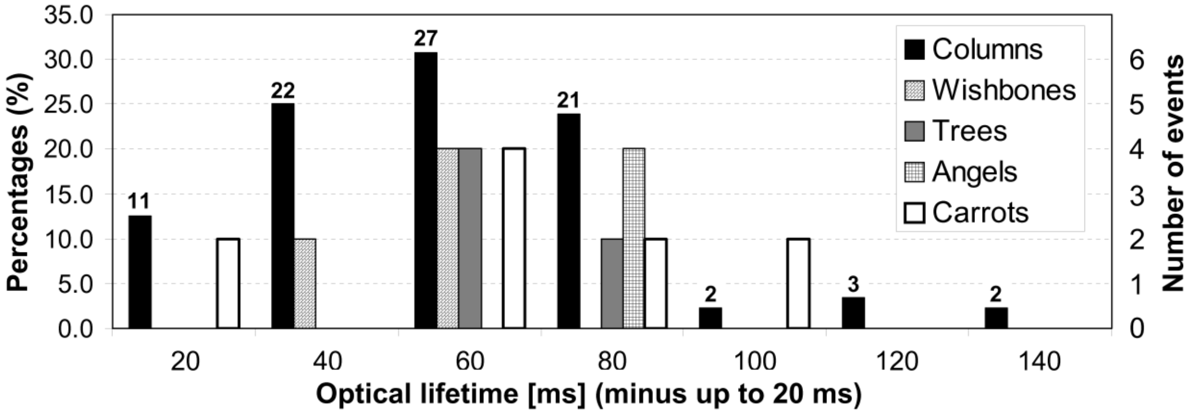


Figure 15. Duration of selected homogeneous events. For columniform sprites, the distribution of durations is plotted. Above each bar, the corresponding number of events is written. The number of events is plotted for other morphological classes.

Regarding the homogeneous cases involved in the duration analysis, Figure 15 shows the distribution of durations for column sprites, while the number of cases in which the event was detected to last for the given milliseconds (minus up to 20 ms) is plotted for the rest of identifiable morphological types. The number of columniform events (88, including 7 singles) is predominant among the involved homogeneous cases (103), while the occurrence of other types is scarce (3 wishbones, 3 trees, 2 angels, 5 carrots, 1 other, and 1 ambiguous). The relation of different morphological types with the event duration, therefore, could not be investigated for homogeneous events in general. On the other hand, this event set provides a good ground to examine the possible relationship of sprite features with the event duration because of the greater level of type homogeneity.

Columniform sprites occur the most frequently also in the selected mixed clusters (120/135 events), but sprites of other morphological classes could also be found in higher number here (Table 1) than among homogeneous events. Plotting the duration distributions for mixed events with and without any member of a given basic sprite type shows that events containing column, angel, or carrot sprites can last longer than events lacking these types (Figure 16). While the presence or absence of wishbone sprites do not seem to indicate any characteristic pattern in the distribution of durations, tree forms, on the contrary, do not tend to occur with long lasting events (Figure 16c). Note that clusters containing tree, angel, or carrot sprites do not have very short durations (Figure 16cde).

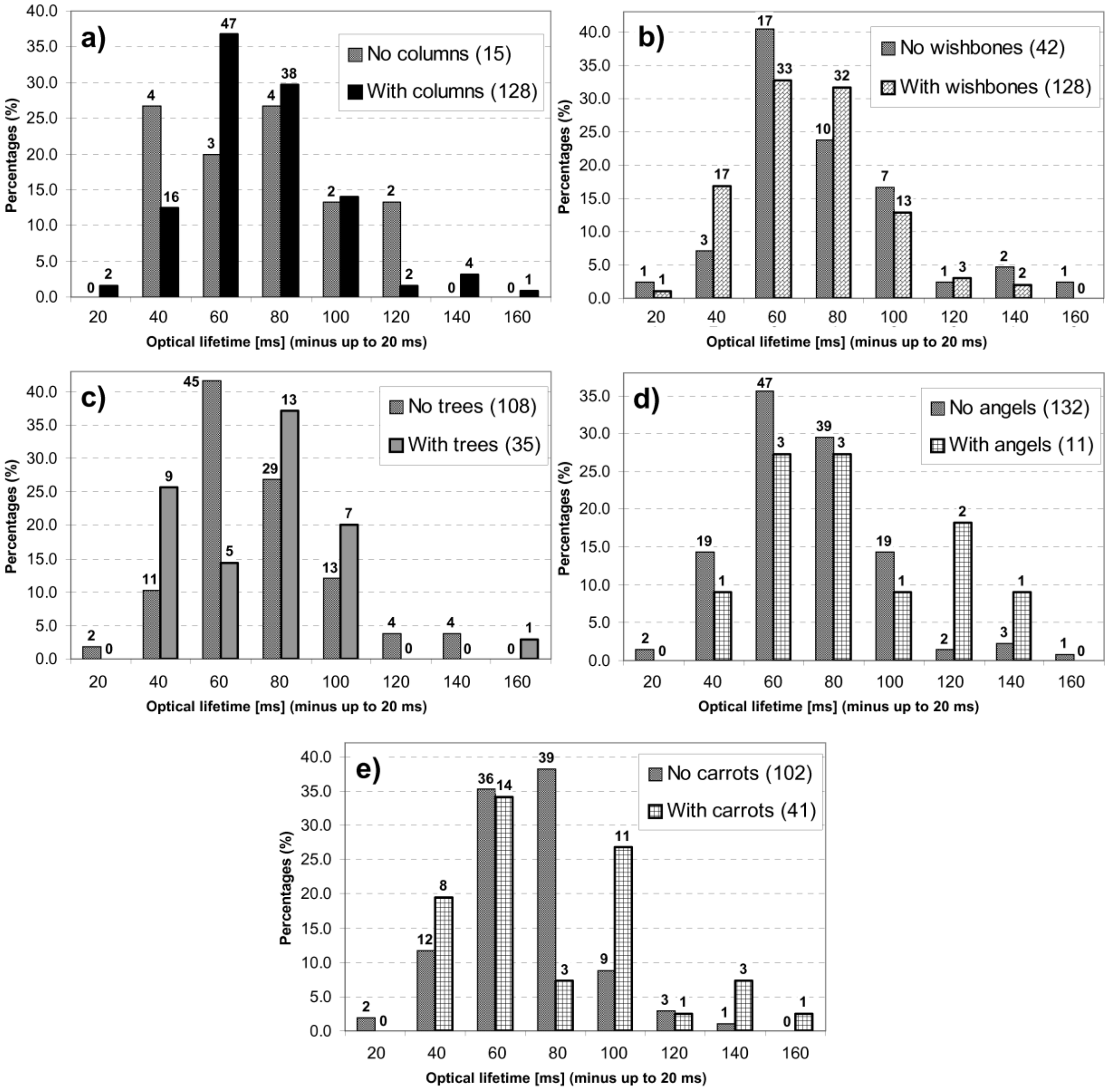


Figure 16. Duration of mixed cluster events with sprites of different morphological types. On top of each bars, the numbers of the corresponding cases are plotted.

5.4.4. Optical duration of the event and the presence of occasionally observable sprite features

On Figure 17, the distributions of durations in homogeneous sprite clusters are compared for events in which a given feature was or was not observed. Among various types of beads, only spots were included in this analysis because of their better observability.

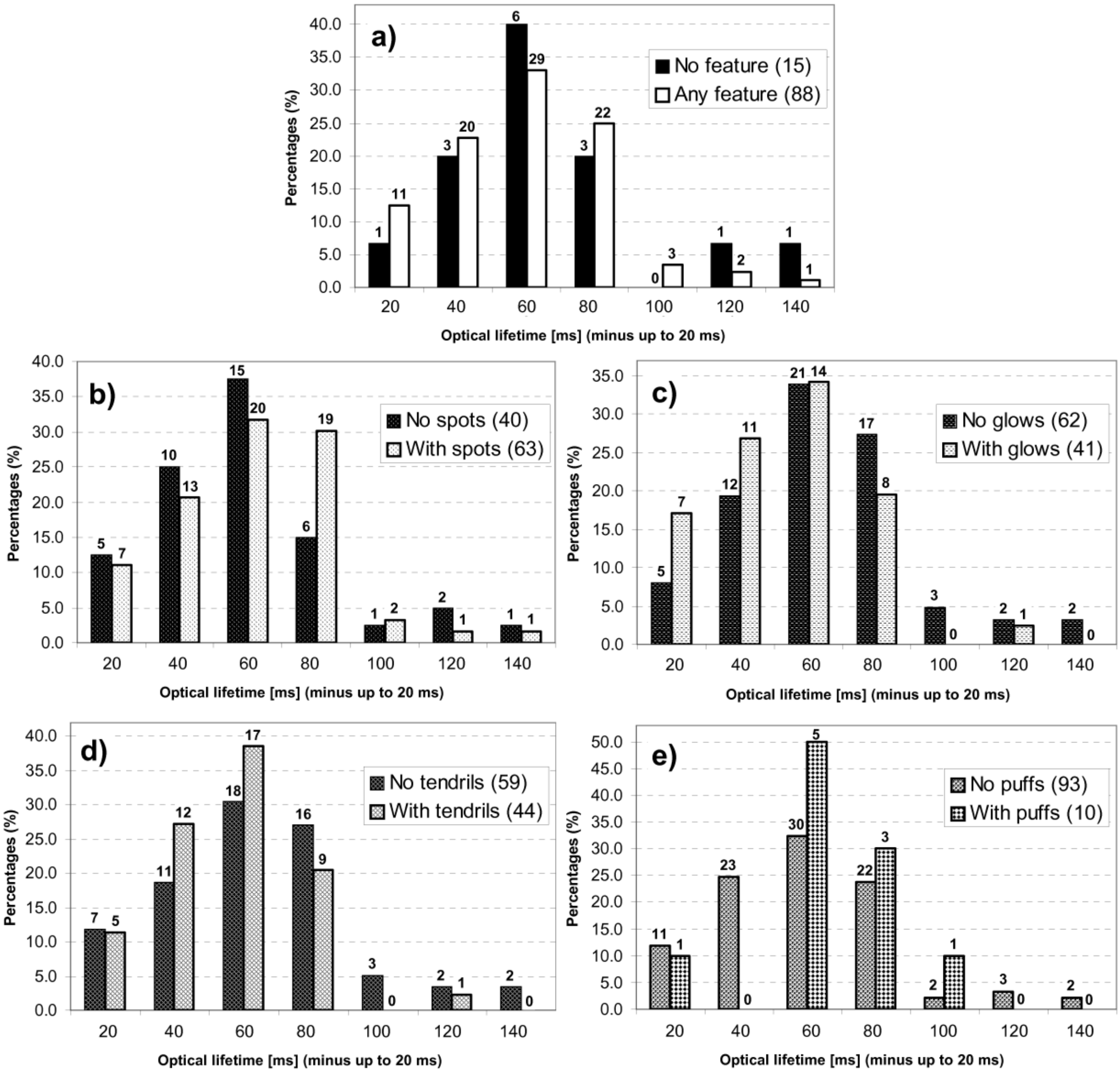


Figure 17. Duration of events with occasionally observable sprite features in homogeneous events. On top of each bars, the numbers of the corresponding cases are plotted.

It is apparent that the peak of the distributions of the durations is not affected by the presence of different sprite features, but the high end of the distributions is less populated if tendrils or glows are present (Figure 17cd). These results about the homogeneous events are practically mirror characteristics of column sprites, since 85% of the homogeneous events in the duration analysis were contained this sprite type. Both glows and tendrils were observed in 47% (82 from 175 cases) of events of columniform sprites showing any of these features. The simultaneous appearance of tendrils and glows is, on the other hand, characteristic to jellyfish sprites, which tend have shorter optical duration. This suggests that the appearance of glows and tendrils is related to the duration of the optical emission at least in column sprite events. On the other hand, the peak of the distribution is more extended towards longer event durations on occurrences of spots (Figure 17b).

Distributions of durations of events in which different sprite features appeared or did not appear have been compared for mixed sprite clusters, too. The most frequent optical lifetime was around 60 ms in almost every case. Only in presence of glows, durations of ~80 ms were observed more frequently. Except for spots, the appearance of a sprite feature widened the peak of the distribution. Event durations from 40 ms up to ~100 ms were observed more frequently than other durations outside this interval if glows, puffs, or tendrils were present. Duration distributions of cases showing any of the occasionally observable features are found to be more extended towards longer lasting events. Cases with optical lifetimes of ~160 ms were observed only when either spots or tendrils or puffs or glows appeared. Otherwise, the comparisons do not indicate such trends in event durations with the appearing individual features as in cases of homogeneous events.

6. Summary and conclusions

At the evaluation of the findings in this analysis, it must be considered that the classification of the events has been carried out by visual inspection, so it is subjective. Nevertheless, high number of events could be sorted unambiguously by the defined criteria, so conclusions drawn from the distributions of sprites in the defined categories are expected to represent real trends.

Discussed characteristics of sprites observed in Central Europe in the 2007-2009 period compared to reports of other observations indicate that this TLE type has the same set of forms and occasionally observable features probably all over the world. Although the variety of the sprite forms is vast, main morphological classes can be set up. Most sprite entities can be sorted into these classes by the final form of the emission in their body as it appears on long exposed video frames or on peak-hold images. Note that environmental conditions determining the region of the brightest emissions on such records are yet to be determined. Basic (i.e. most frequently occurring) sprite forms are the column, wishbone/tree, angel, and carrot.

Probable time sequences of streamer propagation directions can be associated with most members of each morphological class (Figure 18). The assigned time sequences have been confirmed by high-speed video records in some cases of column and carrot sprites, while they remain to be verified for events in other morphological classes. Some of the basic forms can possibly be developed via different physical processes and each mechanism of such may have different sequences of inferred directions of streamer propagation. Additionally, various odd shapes either not fitting to any basic morphological class or bearing characteristics of more classes simultaneously can also be observed indicating that the initiation and formation of sprites can take place in many ways more of which are not fully explored to this date.

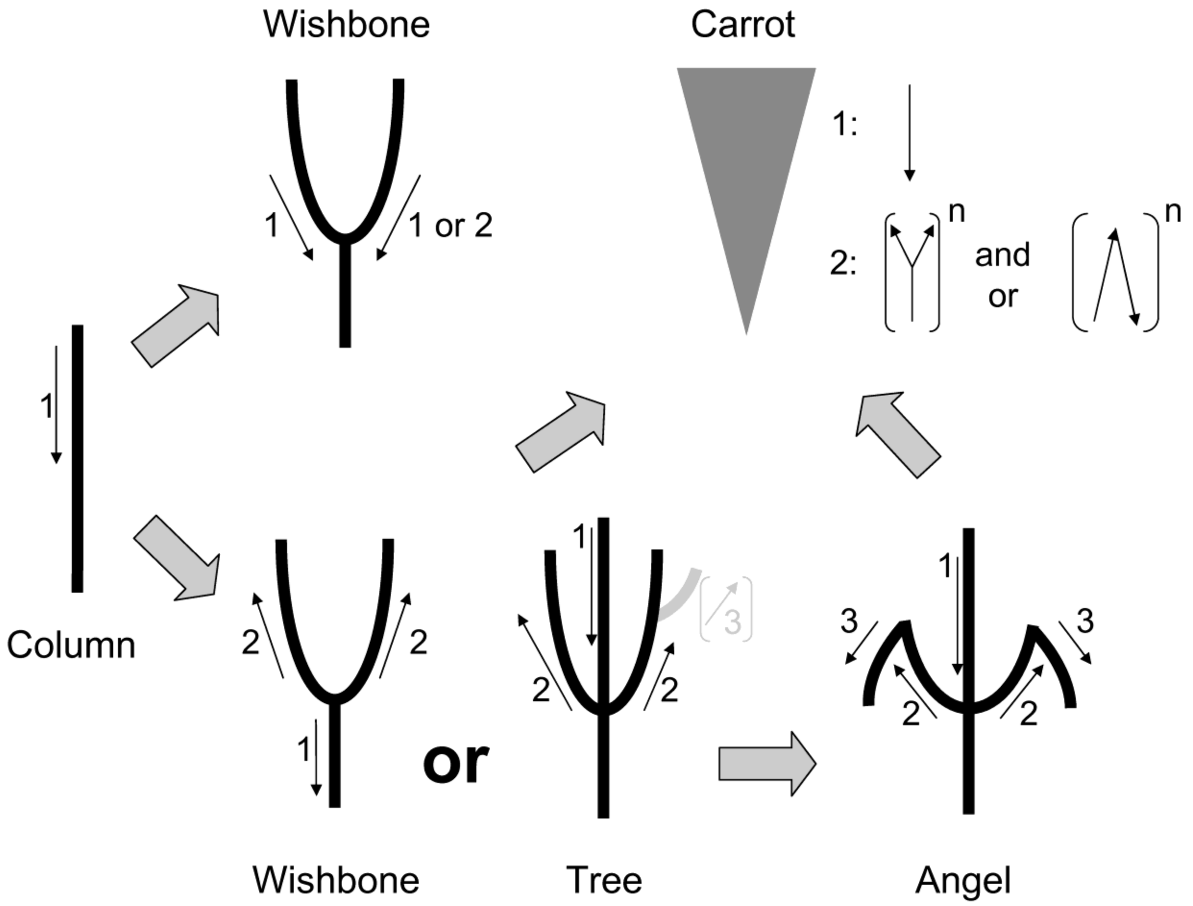


Figure 18. Characteristic forms of the body of sprites in the main morphological classes. Thin arrows show the associated directions of streamer propagations and corresponding numbers indicate the sequence of time periods in which the associated propagations occur. Note that time periods labeled by the same numbers at a figure may not be fully identical. See the text for details. Thick arrows indicate the potential evolution of sprite entities.

High-speed video observations as well as sprite formation intercepted by frame or field separators in conventional frame rate records show that complex sprite shapes develop from simpler structures. Different established morphological types can be recognized at subsequent stages in various cases of sprite development and these can be put in a probable time sequence ending in a final form. Such sequences are for example the column-carrot or the column-wishbone/tree-angel (Figure 18, Figure 19) evolution time lines. According to the observations, this evolution of a sprite element, if it ever happens, takes place in the first few milliseconds of the event. On the other hand, even the most simple column form can remain luminous for several tens of milliseconds (Figure 15) without any significant change in its shape. This indicates that the final form of the sprite and the duration of the emission are determined by different physical (and possibly chemical) processes occurring on different time scales. Environmental factors determining the form and optical duration of a sprite are yet to be identified.

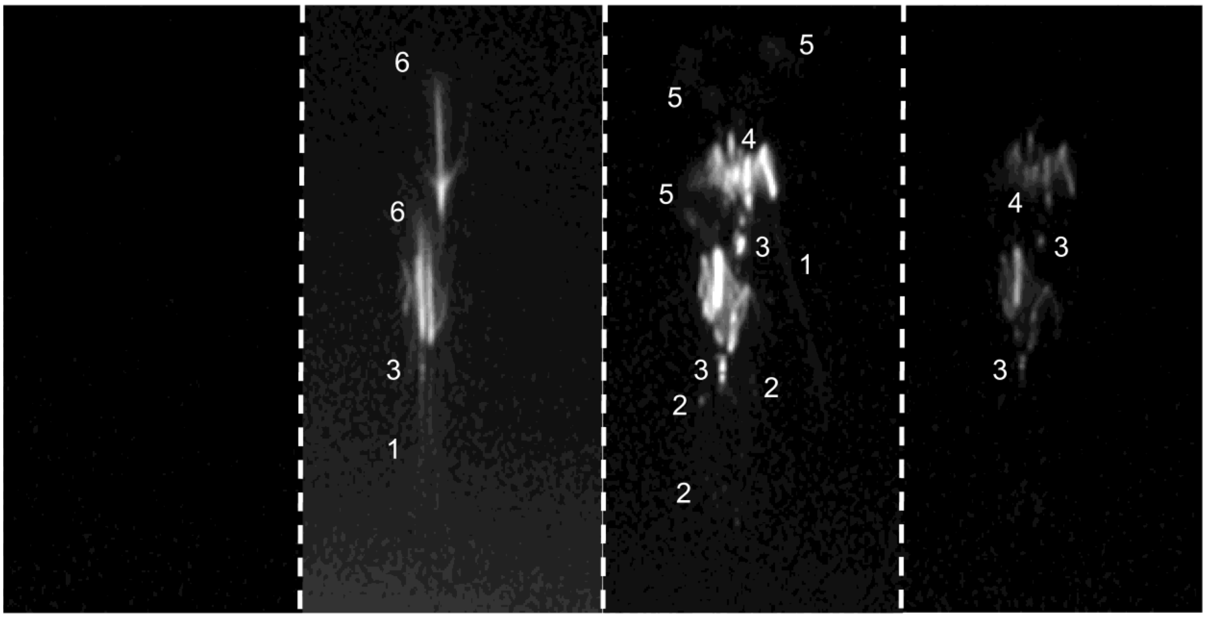


Figure 19. Consecutive video frames (by 20 ms) of the „morphing" sprite event observed above Hungary. Numbers indicate occasionally observable sprite features: 1-tendrils; 2-beads along the tendrils; 3-spots; 4-beads in the sprite body 5-puffs, 6-glows. Note that the glows are rather weak and merge in the region of faint puffs. First video field corresponds to 20:48:18.667 UTC, 10. Aug., 2007.

With sprites in each morphological class, similar occasionally observable features may appear. Such features are the sprite tendrils, puffs, glow surrounding the body of the sprite, and brighter, more localized emission regions (i.e. beads) of longer optical lifetime in and around the sprite. Some of these beads called spots in this study have been distinguished by their characteristic optical properties and location at the base of a sprite entity.

Also the number of sprite entities appearing in an event shows considerable variety. Statistical analysis shows that most of the sprites in Central Europe appear in clusters rather than alone, and that more than half of the sprite clusters contain sprites of more morphological classes. The most frequently observed type has been the column.

Two special subclasses of sprite clusters have been distinguished. Jellyfish sprites are bright clusters of more elements. The elements in jellyfish clusters are frequently of simpler forms (columns or wishbones) and characteristically feature long, bright tendrils as well as extended bright glows around their body. These events tend to have shorter optical lifetimes. It was found that sprite events with a high number of elements do not have long lifetimes (i.e. >80 ms) in general.

The other special group among sprite clusters is the set of dancing sprites. A dancing sprite probably consists of more regular sprite events the appearances of which, however, seem to be connected. The nature of this connection is yet to be explored and quantified. Sprite elements in dancing events are usually of similar morphological type, but one or few larger, brighter and more complex element may show up in the sequence of appearing emissions.

The statistics of occurrences showed that there is no apparent connection between the main form of the appearing sprites and the total optical duration of the event. On the other hand, type variety in a sprite event seems to be in connection with the optical lifetime of the event. Less homogeneous sprite clusters have been found among long duration events, and mixed sprite clusters generally do not have very short lifetimes. The statistically observed shorter duration of homogeneous sprite clusters refers mostly to columnar sprites the number of which is predominant among the observed homogeneous events. Columnar sprite events with long optical duration generally have not found to occur when tendrils and/or glows are present. The origin of this correspondence is yet to be explored.

The low glow/puff occurrence rate among single sprite events and the corresponding high value among homogeneous events suggest that the body of singly appearing sprite entities tend to be below the region of transition zone (Pasko et al., 1998), while the top of sprite elements in homogeneous clusters more frequently reach up into this region. On the other hand, the lack of unambiguously detected glows in angel sprites and frequent occurrence of puffs in angel and carrot sprites indicate that the body of angel and carrot sprites tends to form within the streamer zone below the transition zone. This stands in good agreement with the theoretical predictions by Rycroft and Odzimek (2010).

While sprites may not affect our global environment in a great level (Pasko et al., 2012), they can play an important role in exploring the structure and dynamics of electric as well as other physical processes either in thunderstorms in the troposphere, in the mesosphere, and probably in the lower ionosphere, too. The physical connections between the directly perceptible features of sprites considered in this study (i.e. number of elements, shape, sprite features, and duration) and the characteristics of the environment of sprite production are mostly unexplored currently. Simultaneous and independent optical observations of high time and image resolution, as well as dynamic mapping of the related electric processes in thunderstorms are needed to answer the numerous questions raised by the results of this analysis.

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