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High-speed intensified video recordings of sprites and elves over the western Mediterranean Sea during winter thunderstorms

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[1] We report the first intensified high-speed video images of elves, sprites, and halos observed in Europe. All the events corresponded to winter season thunderstorms over the Mediterranean Sea. The observations comprise many elves generated by both cloud-to-ground lightning current polarities. In 8 of the 14 sprite observations we observed an elve previous to the sprite. In three cases we observed also an elve quickly followed by a halo and a sprite. In several observations we observed lightning light before the mesospheric transient luminous event. We present a case where the lightning from cloud tops was visible during the entire event. Thanks to the high-speed videos and their resolution and low intensifier phosphor persistence we analyzed the timing distribution of the development phase of sprite elements, the persisting luminosity phase, and the total duration. Finally, we summarize one particular observation where a streamer collides and bounces with a previous formed column; it may be a new phenomenon of collision between an existing column body that interacts with a later streamer point-like tip which is not merged and attached.

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1. Introduction

[2] Sprites and elves are transient luminous events (TLE) that occur above thunderstorms. Sprites occur at altitudes of ~40 to 90 km [*Sentman et al.*, 1995] and are commonly associated with positive cloud-to-ground (+CG) lightning discharges [*Boccippio et al.*, 1995]. Elves are optical emissions at the bottom edge of the ionosphere (altitude ~90 km) propagating outward like an expanding ring [*Fukunishi et al.*, 1996]. Elves are associated with cloud-to-ground (CG) lightning of either polarity [*Inan et al.*, 1996; *Cho and Rycroft*, 1998; *Füllekrug et al.*, 2006].

[3] Ground observations of sprites and elves have been conducted in Europe since the summer of 2000 [*Neubert et al.*, 2001]. The cameras employed in these campaigns have been basically sensitive video cameras with 25 to 50 frames per second (fps) [*Neubert et al.*, 2008]. While, in U.S., during the last decade high-speed video cameras were employed for TLE recordings [i.e., *Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000; *Moudry et al.*, 2003; *Marshall and Inan*, 2005; *Cummer et al.*, 2006; *Stenbaek-Nielsen et al.*, 2007; *McHarg et al.*, 2007; *Li et al.*, 2008; *Li and Cummer*, 2009], it has not been since December 2008 when the first high frame rate video recordings have been carried out in Europe. High-speed video recordings have been used to resolve the temporal evolution of sprites and elves and specially streamer propagation and velocities in sprites.

[4] In this paper we report the first high-speed video recordings of sprites and elves obtained in Europe. All the observations were made during three nights and all the events are related to winter thunderstorms over the Mediterranean Sea. We first report the resume of the cases where sprites appear after elves. High video frame rates allow us to investigate the time differences that are found between the detection of lightning, the lightning light visible at the video images and the first sign of the sprite. Additionally, we will summarize the common features of cases of simultaneous halos and sprites. Then we compute durations of two sprite phases: development and persistence. After general features of sprites we summarize the recorded elves. Finally we describe two observations, one is an observation with an elve, halo and sprite and illuminated cloud top, the second is a new phenomenon of a sprite streamer bouncing after being attracted to a previous formed column. The reported observations here provide time-space characteristics of TLEs that occurred over sea during winter of temperate regions.

[5] During 2 December 2008 a total of 4 sprites and 14 elves were recorded with the high-speed video instrument.

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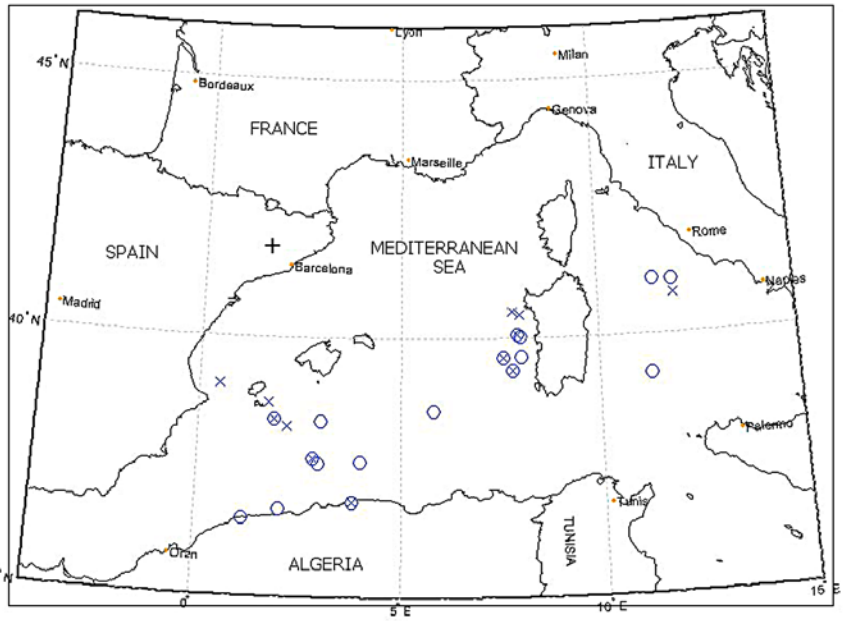

Figure 1. Locations of the parent lightning of observed sprites (crosses), elves (circles), and events in which elves and sprites occurred successively (crosses within circles) during 2 December 2008, 10 December 2008, and 20 January 2009.

In each of these four sprite events a previous elve was observed. On 10 December 2008 a total of 12 sprites were high-speed recorded. In that night also many elves were observed but we only kept 8 cases. The last observation night was during 20 January 2009. In that night only 2 sprites and 3 elves were recorded at high frame rates. In all of these nights thunderstorms were localized over the Mediterranean Sea. Figure 1 presents the locations of the parent lightning associated to sprites and elves.

2. Description of Data

2.1. High-Speed Video

[6] The high-speed video instrument was a Phantom v7.3 CMOS camera attached to a gated image intensifier with 1 μs phosphor persistence. This assembly allowed to record at frames rate of 6888 to 15037 fps. A 85 mm f/1.4 lens was used to register detailed images for far events and a 50 mm f/1.4 lens were used for a more wide-angle view of closer events. The instrument was GPS time synchronized allowing time stamping within 2 μs resolution. In the same mount of the instrument a second low-light sensitive video camera at 25 fps were installed in order to trigger the high-speed system.

2.2. Lightning Data

[7] Lightning data were provided by the LINET network [*Betz et al.*, 2004]. At that time, the network was composed by 100 VLF/LF sensors installed over Europe. The network provided time, location and current estimation for both classified cloud-to-ground (CG) and intracloud (IC) detections. Additionally, in some observations, data from Meteorage lightning detection network which is similar to the NLDN [*Cummins et al.*, 1998] was used as redundancy.

3. Meteorological Situation

[8] On 2 December 2008 a large upper trough filled with cold air (500 hPa temperature around −32°C) entered the western Mediterranean Sea during the previous night (1–2 December), increasing the temperature lapse rates and instability over the comparatively warm seawater (200–500 J/kg Convective Available Potential Energy, CAPE). The cold front was situated over central Italy. Under the influence of an extension of higher pressure at surface level the flow was north-northwesterly, and air stabilized from the north during the evening. Showers and thunderstorms developed along convergence lines in the wake of the Balearic islands and in the coastal convergence zone of Algeria. The storms tended to be small and scattered, more clustered along the Algerian coast. Maximum cloud tops were 6–7 km. The storms produced many elves and occasionally sprites at 400–600 km range from the camera. The 2 m temperature was 11°C with a dew point of 4°. At 850 hPa (~1400 m) it was near −1°C. A similar situation occurred one week later, when another mass of cold air arrived from the north. On 10 December 2008 the coldest upper 500 hPa temperature of −33°C was located over the Balearic islands. 100–300 J/kg CAPE was present in this region. However, the most unstable area stretched along the east side of the slowly moving cold front, from northeastern Algeria to Sardinia, and the Tyrrhenian Sea, with 700–900 J/kg CAPE and 15 m/s bulk shear vector magnitude between 0 and 6 km, and stronger lifting along the front. This environment was conducive to mesoscale convective systems (MCS). Several MCS developed near Sardinia in the southwesterly flow

during the afternoon and evening. The low-pressure area at the surface was located west of Corsica and Sardinia, causing a northerly flow near the Balearic islands and convergence lines in the lee of orographic features of Catalonia and the Balearic islands. These storms tended to be small with cloud tops of only 4–5 km as is common for winter storms. The storms near Sardinia were MCS with higher tops (km) and much longer life cycle. Both storm areas produced elves and sprites. During the period 2330–0030 UTC very large sprite sequences occurred over the Sardinian system with a northward motion. The 2 m temperature over the western Mediterranean was 7°C with a dew point of 3°. At 850 hPa it was near −3°C around the Balearic islands. In the warmer air mass, 2 m temperature was 10–14° and dew point 9–11°, with 4–5° at 850 hPa. Finally, on 20 January 2009, a very similar situation again, with a large cold upper trough, but this night the Balearic region was at the east flank, T500 near −32°C. The sprite-producing storm developed between Valencia and Ibiza. Many elves were observed in the direction of Bay of Biscay as well. Again, the low level flow was from the north in a slight ridge of high pressure (which is good to keep clouds away from the camera), T850 = −3°, T 2m = 8°, and Td2m = 5°. There was a jet stream with speed greater than 52 m/s at 350 hPa (7 km) CAPE around 300 J/kg and tops up to 6 km.

4. Discussion of the Observations

4.1. Observations of Sprites With an Associated Previous Elve

[9] In eight of the fourteen sprite observations a preceding elve was observed. In most of these cases the sprites appeared at delays shorter than 11 ms. In observations 3 and 11, the delays between elves and sprites were 178 and 59 ms, respectively. In observation 3 light from lightning was observed 8.8 ms before the sprite initiation which denoted that the elve and the sprite observed had different origin during the same or different lightning flash. However, no lightning activities were recorded around that time by both lightning detection networks. In observation 12, a sprite cluster appeared only 0.6 ms after the elve. All these observations were associated to positive cloud-to-ground lightning flashes (+CG). High-speed observations of elves associated with sprites and halos were reported by *Moudry et al.* [2003]. These observations corresponded to thunderstorms over Nebraska (U.S.) and the observed elves were associated with sprites and halos. During Eurosprite campaigns, we rarely observed elves produced by CG parent lightning striking land, our observation of elves seem to be linked to Mediterranean Sea and Atlantic ocean thunderstorms. During 2007 and 2008 Eurosprite campaigns most of the elves observations were concentrated in December.

4.2. Observations With Simultaneous Halos and Sprites

[10] Simultaneous sprite and halos were only present in three observations. No halos alone were observed. In observations 1 and 14 the halos had the same total duration (5.83 ms) while in observation 12 the halo only rested 0.75 ms. In observation 1 the sprites started 1.34 ms after the halo initiation, but in observations 12 and 14 a sprite appeared at the same time as the halo. In observation 12 the halo appeared just after an elve but this observation corresponded to a second sprite cluster in a "dancing" sprite event with three clusters ranging a large area (around 150 km). Thus the elve and the halo occurred only in the second cluster. The lightning location network detected three different +CG flashes associated to each cluster but the halo case presented the biggest peak current.

[11] We have not observed halos alone, in fact, we only observed halos simultaneously with elves and sprites. In these cases the time delay between the elves and the sprites was short (between 0.6 ms to 2 ms) compared with those cases elves and sprites without halos (average 30 ms). Image sequence of observation 14 is displayed in Figure 3.

4.3. Development and Persistence Phases of Sprites

[12] High-speed video recordings allow studying the timing of different phases of the sprite. We distinguished two main stages of every sprite element: development phase and persisting luminosity phase. Streamer phase corresponds to the initial phase where streamers develop. When we define streamer phase, it takes into account the common initial downward streamer that forms the tendrils and the upward streamers that form the commonly named branches. Subsequent streamers in carrot type sprites which move from the top to the bottom part of the sprite body in a side curve path are included in streamer phase. Distribution of streamer phase durations corresponding to individual elements in sprite clusters are displayed in Figure 2a. After streamer phase most of the sprites glow with some persistence with no noticeable moving streamers. These correspond to the end phase of the sprite. Figure 2b plots the distribution of the observed persistence durations in individual sprite cluster elements. Finally the total duration distribution corresponding for each individual element is represented in Figure 2c. A remarkable phenomenon is that even when different elements start at different time in a cluster, the ending time of the persistence is the same for all the elements. It could indicate that this simultaneous ending may be due to the decay of the electric field at that altitude produced by the end of the lightning activity below. The total duration is consistent with the continuing current phase duration in a lightning flash.

4.4. Elves

[13] During the three nights a large proportion of elves were observed. Although the number of observed elves was large, the total number of recordings finally saved with the high-speed instrument was only 26. However, in only 15 of the 26 observed elves the detected parent lightning occurred before the elve. In 3 cases the parent lightning was not detected while in 8 observations the parent detected lightning lagged the elve for several to few tens of milliseconds. These lightning detections correspond to those given by the two lightning location networks. It is important to point out that the cases where the lightning was well correlated with the elves their currents were considerably high. Eight cases presented positive peak currents with mean values of 193 kA while six cases had negative currents with −155 kA of mean peak current. These peak currents are much higher than in those 8 cases where the lightning time lags the elve observation.

[14] In our observations, most of the elves appeared alone without a noticeable halo or sprite. As shown in Figure 1, all

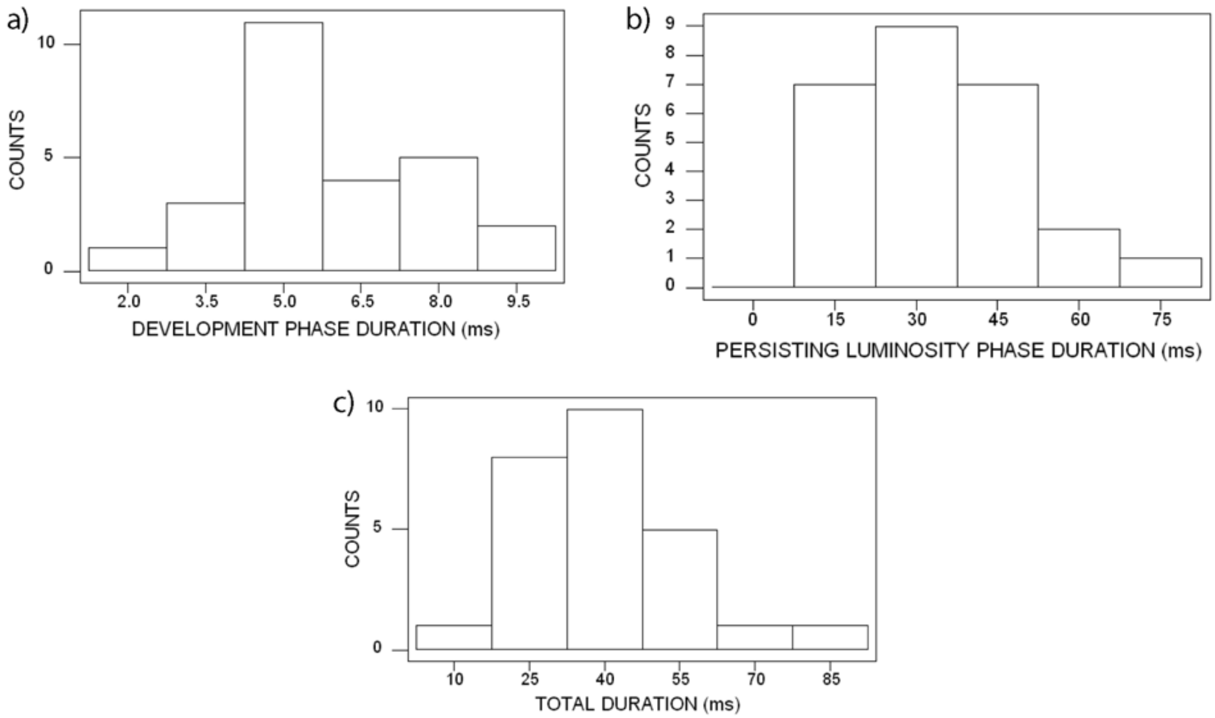

Figure 2. (a) Distribution of development phase duration for individual elements. (b) Distribution of the persisting luminosity phase duration for individual sprite elements. (c) Distribution of the total duration of individual sprites.

the events were related to sea lightning with either polarity. Moreover, by selecting those cases with video screen resolution of 800 × 600 and 85 mm f/1.4 lens, the average duration of the elves crossing the screen ranged from 1.6 ms to 2.8 ms.

4.5. Observations of Lightning Flash Light, Elves, Halos, and Sprites

[15] In five of the fourteen observations scattered lightning flash luminosity previous to sprite initiation was observed in the lower part of the high-speed video frames. These cases corresponded to those where the parent lightning occurred in a range close to 400 km from the observation point. The time difference between the times assigned by the lightning detection network and the lightning light at the camera ranged from 1.17 ms to 74 ms while the time differences between the lightning light and the sprite ranged from 2.8 ms to 35.8 ms.

[16] Apart from the observations of lightning light, in seven observations an elve was present before sprites and in two observations an elve, a halo and a sprite were observed in the same record. But in only one observation (14) these three phenomena were observable simultaneous with lightning light from the cloud top. Figure 3 shows a selection of 12 frames of that case. At t = 0 ms a weak lightning light was detected which corresponded at time of de parent positive CG flash. Linet reported a +CG flash with peak current of 272.8 kA which is extremely high compared to the median values of the positive lightning peak currents. After 1.473 ms the light was becoming more intense until t = 1.772 ms where the light saturated the intensifier and, at that moment, distinguishable light of the propagating elve was first detected. At time 3.117 ms the elve reached the lower half part of the video frame. Just after the elve a halo and sprite started to develop. Both started just at the same time but sprite elements seemed to develop side of halo. At frame 6.875 ms the halo was not longer present but still some development phase of some sprite elements were active. The persistence phase of all the sprite elements started at t = 13.473 ms up to t = 31.173 ms. The persistence phase of the sprite cluster started when the scattered light from the lightning flash decayed but little luminosity was still detectable until 9 ms before the last sign of sprite in the screen at t = 31.173 ms.

[17] The evolution of lightning light in observation 14 and the delays between the time reported by the lightning detection network and the observed brightest lightning suggest that intracloud activity after the return stroke may play an important role for sprite initiation and evolution as suggested by *Ohkubo et al.* [2005] and *van der Velde et al.* [2006, 2009]. It is interesting to point out that the sprite development phase in observation 14 ended when the cloud light decreased. However, little appreciable light was detectable for 9 ms. These observation suggest that the development stage may be related to the period of continuing current and the sprite have persistence until the electric field decreased at its altitude to a certain threshold. Intracloud activity after continuing current to ground may help to enlarge the persistence duration.

4.6. Case of a Tendril Attracted to a Previous Column

[18] Observations of tips of downward moving sprite tendrils which are attracted and, in some cases collide with adjacent streamer channels were recently reported by

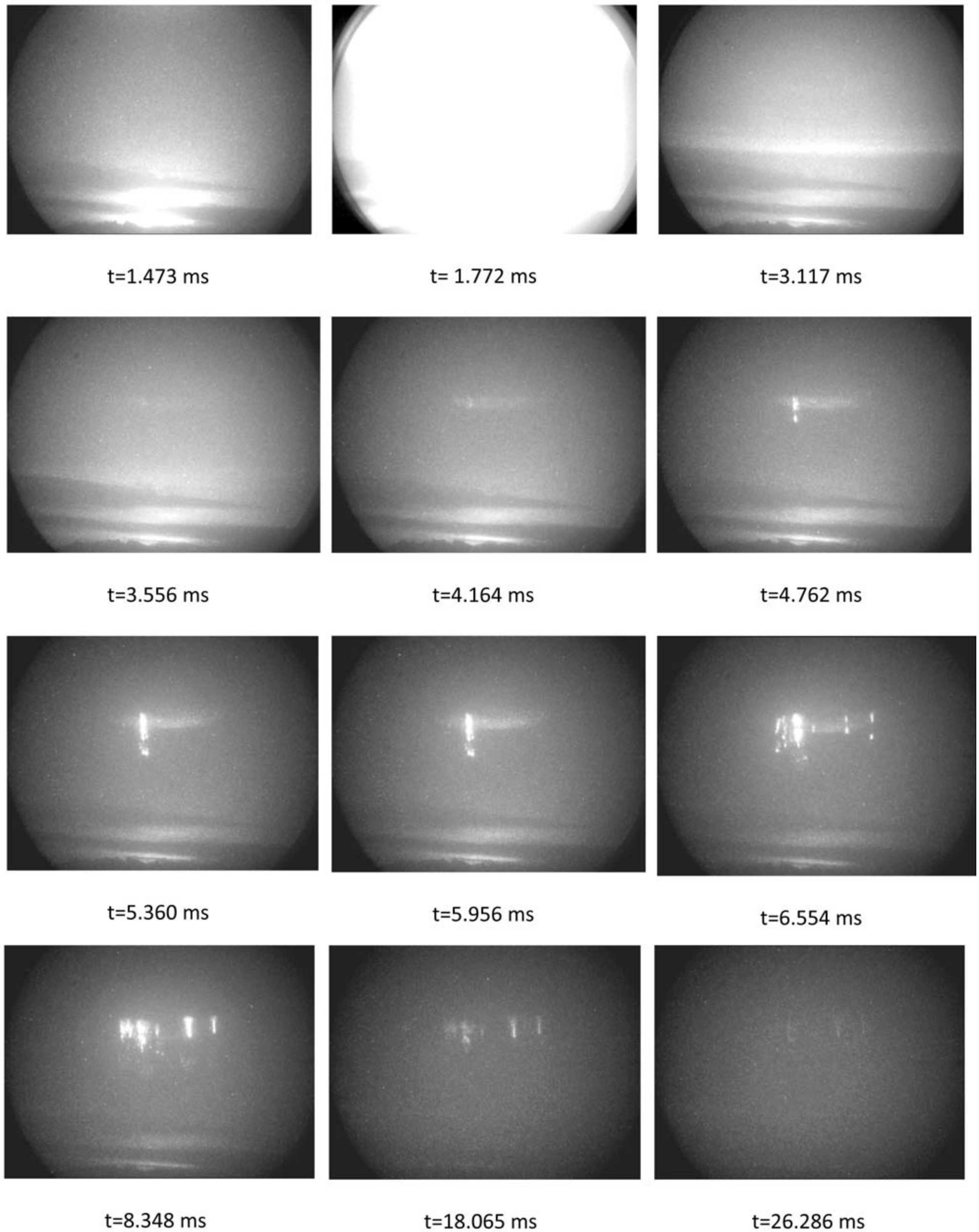

Figure 3. High-speed images from observation 14 (20 January 2009). The time of each image is referenced to the time of the detected parent lightning.

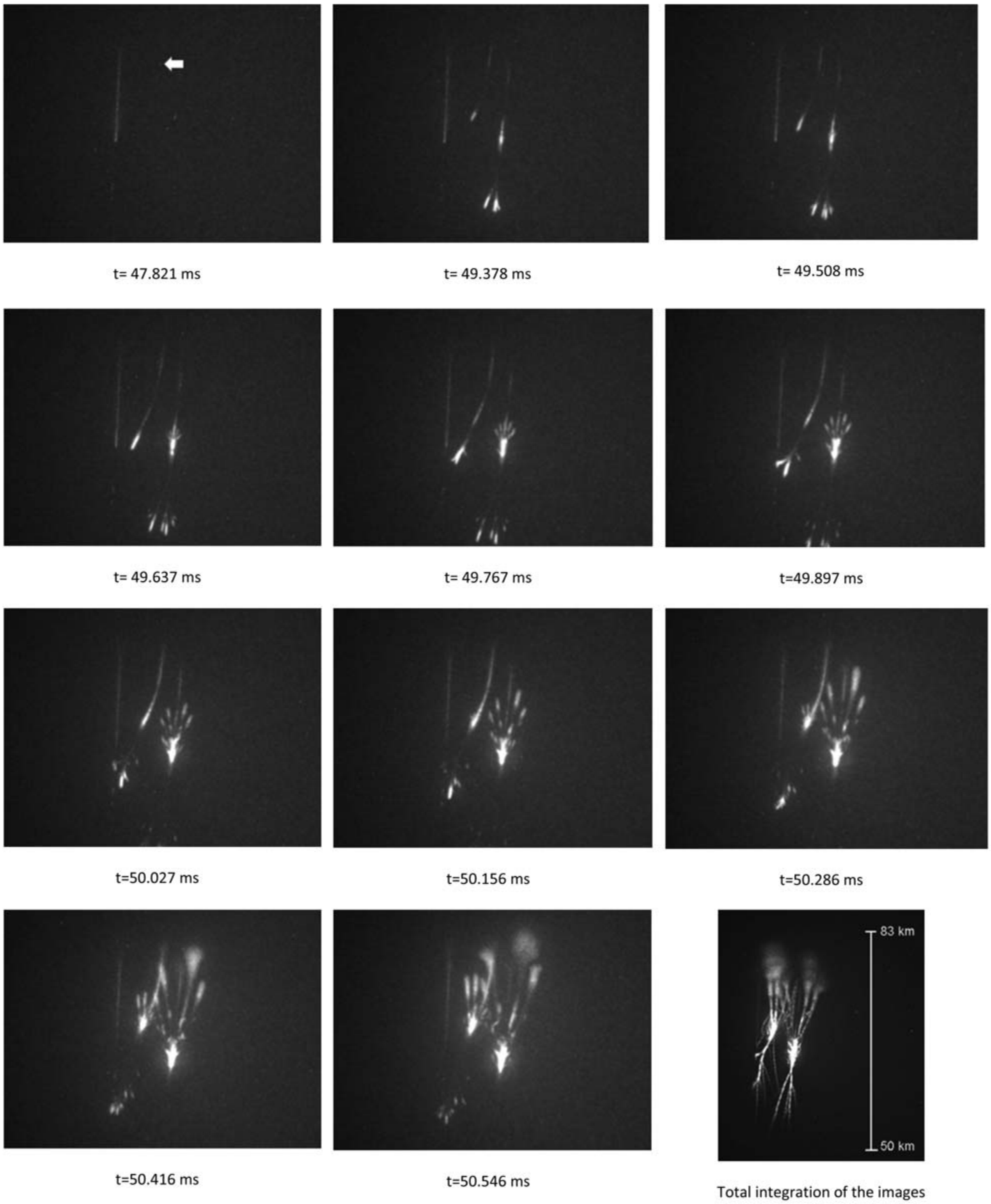

Figure 4. High-speed images from observation 7 (10 December 2009). The time of each image is referenced to the time of the detected parent lightning. The arrow indicates the first sign of the streamer tip of the central sprite element. The last image corresponds to the composite image of all the frames that composes the video.

Cummer et al. [2006]. We observed a similar phenomenon but in our observation 7, a downward moving tendril is attracted to a column which developed 26 ms before and not keeps merged or attached. Moreover, no long-persisting sprite beads appeared at the point of collision.

[19] In observation 7 the first sign of a single column appeared 47.82 ms after a +CG with 26.7 kA of peak current located at 409 km from the observation point and 20.37 ms after some light of a lightning flash was detected in the video images. A sequence of images corresponding to observation 7 is displayed in Figure 4. The event was composed by a single column and two carrot-like sprite elements. The column started with a point-like illuminated streamer tip propagating individually downward for ~3 ms, then after ~19 ms the column was completed (at t = 47.821 ms in Figure 4). ~3 ms later, both carrot sprite elements started also from a downward point-like streamer tips. The mid element tendril that was being developed at the right side of the column (see frames t = 49.378 ms to 49.767 ms in Figure 4) was deflected toward the non illuminated part of column below altitude. At t = 49.767 ms the tip branched in two parts. One of the new tips moved toward the column and collided. The collision was in a bouncing like because, after collision that tip continued sliding and splitting downward over the column. After the first splitting (t = 49.767 ms) the other tip formed the longest downward streamer which continued propagating downward but close and parallel to the column profile until it reached the lowest altitude of the column. At that altitude, the downward tendril avoided the column tip rounding it and then continuing vertically (see images from t = 50.156 ms to t = 50.546 ms in Figure 4).

[20] As pointed by *Cummer et al.* [2006] this attraction could be due to electrostatic forces between streamer tips and, in our case, the body of the column. In our observation the collision is between a previous column and a later sprite element. We suggest that the downward moving streamer tip has positive charge and the column may be considered as quasi-neutral plasma where the downward streamer tip could induce negative charge while is approaching the column body. This induced charge could be the cause of the deflection of the streamer tip toward the column. When the tip interacts with the column both may neutralize charge and the lower part of the column body could keep neutral or slightly positive. This could be the effect that the colliding tip and the longer streamer do not follow the column core. Regarding the column extremities we assume the upper column tip to be negative and the lower tip positive.

5. Conclusions

[21] Here we have presented the first high-speed videos of TLEs recorded in Europe. Additionally all the events corresponded to winter season thunderstorms over the Mediterranean Sea. We confirmed the dramatic difference between thunderstorms over sea and over land referring to the elve production. In previous Eurosprite campaigns we rarely observed elves over land, most of elves observations belong to winter thunderstorms over sea. We observed elves alone and associated to both polarities of CG flashes. Only associated to positive CG flashes we observed some cases where elves typically appeared ~11 ms before sprites. All the observations were halos appeared an elve occurred before 2 ms of the initiation of the halo and the sprite elements. In our observations most of the sprites, columns and carrot-like types, were initiated by downward point-like streamer tip before the upward development. In those observations of halos, the sprites appeared to be initiated downward and upward without initial single point-like streamer type. It may indicate substantial different electromagnetic environment for those sprites occurred with and without halos. Finally, sprites associated with halos seemed to be located in front or in a side of the halo. The halo center looks to be more related to the center of the previous observed elve.

[22] Regarding sprite element timings, we analyzed the time distribution of the development phase, persistence phase and the total duration. We called the development phase to define the time in which moving streamers are detected. The typical duration of the development phase is about 5 ms while the persistence phase where no streamer movement is detectable ranges from ~7.5 ms to ~80 ms with a typical value about 30 ms. Finally the typical total duration of sprite elements is about 40 ms ranging from less than 10 ms to 90 ms.

[23] The behavior of the lightning light from a cloud tops during an event in which an elve, a halo and a sprite were observed suggest that intracloud activity before, during and after continuing currents to ground could play an important role in the sprite initiation and development.

[24] We presented a new phenomenon where a downward point-like streamer collides and bounces with a previous formed column, it may be a new phenomenon of collision between an existing column body that interacts with a later streamer point-like tip which are not merged and attached.

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References

Betz, H.-D., K. Schmidt, P. Oettinger, and M. Wirz (2004), Lightning detection with 3-D discrimination of intracloud and cloud-to-ground discharges, *Geophys. Res. Lett.*, *31*, L11108, doi:10.1029/2004GL019821.

Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. Baker, and R. Boldi (1995), Sprites, ELF transients, and positive ground strokes, *Science*, *269*, 1088–1091, doi:10.1126/science.269.5227.1088.

Cho, M., and M. J. Rycroft (1998), Computer simulation of the electric field structure and optical emission from cloud-top to the ionosphere, *J. Atmos. Sol. Terr. Phys.*, *60*, 871–888, doi:10.1016/S1364-6826(98)00017-0.

Cummer, S. A., N. Jaugey, J. Li, W. A. Lyons, T. E. Nelson, and E. A. Gerken (2006), Submillisecond imaging of sprite development and structure, *Geophys. Res. Lett.*, *33*, L04104, doi:10.1029/2005GL024969.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res.*, *103*(D8), 9035–9044, doi:10.1029/98JD00153.

Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U. Inan, and W. Lyons (1996), Elves: Lightning-induced transient luminous events in the lower ionosphere, *Geophys. Res. Lett.*, *23*, 2157–2160, doi:10.1029/96GL01979.

Füllekrug, M., E. A. Mareev, and M. J. Rycroft (Eds.) (2006), *Sprites, Elves and Intense Lightning Discharges*, 398 pp., Springer, Dordrecht, Netherlands.

Inan, U. S., V. P. Pasko, and T. F. Bell (1996), Sustained heating of the ionosphere above thunderstorms as evidenced in "early/fast" VLF events, *Geophys. Res. Lett.*, *23*(10), 1067–1070, doi:10.1029/96GL01360.
Li, J., and S. A. Cummer (2009), Measurement of sprite streamer acceleration and deceleration, *Geophys. Res. Lett.*, *36*, L10812, doi:10.1029/2009GL037581.
Li, J., S. A. Cummer, W. A. Lyons, and T. E. Nelson (2008), Coordinated analysis of delayed sprites with high-speed images and remote electromagnetic fields, *J. Geophys. Res.*, *113*, D20206, doi:10.1029/2008JD010008.
Marshall, R. A., and U. S. Inan (2005), High-speed telescopic imaging of sprites, *Geophys. Res. Lett.*, *32*, L05804, doi:10.1029/2004GL021988.
McHarg, M. G., H. C. Stenbaek-Nielsen, and T. Kammae (2007), Observations of streamer formation in sprites, *Geophys. Res. Lett.*, *34*, L06804, doi:10.1029/2006GL027854.
Moudry, D., H. Stenbaek-Nielsen, D. Sentman, and E. Wescott (2003), Imaging of elves, halos and sprite initiation at 1 ms time resolution, *J. Atmos. Sol. Terr. Phys.*, *65*, 509–518, doi:10.1016/S1364-6826(02)00323-1.
Neubert, T., T. H. Allin, H. Stenbaek-Nielsen, and E. Blanc (2001), Sprites over Europe, *Geophys. Res. Lett.*, *28*(18), 3585–3588, doi:10.1029/2001GL013427.
Neubert, T., et al. (2008), Recent results from studies of electric discharges in the mesosphere, *Surv. Geophys.*, *29*, 71–137, doi:10.1007/s10712-008-9043-1.
Ohkubo, A., H. Fukunishi, Y. Takahashi, and T. Adachi (2005), VLF/ELF sferic evidence for in-cloud discharge activity producing sprites, *Geophys. Res. Lett.*, *32*, L04812, doi:10.1029/2004GL021943.
Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner (1995), Preliminary results from the Sprites94 Aircraft Campaign: 1. Red sprites, *Geophys. Res. Lett.*, *22*(10), 1205–1208, doi:10.1029/95GL00583.
Stanley, M., P. Krehbiel, M. Brook, C. Moore, W. Rison, and B. Abrahams (1999), High speed video of initial sprite development, *Geophys. Res. Lett.*, *26*(20), 3201–3204, doi:10.1029/1999GL010673.
Stenbaek-Nielsen, H. C., D. R. Moudry, E. M. Wescott, D. D. Sentman, and F. A. Sabbas (2000), Sprites and possible mesospheric effects, *Geophys. Res. Lett.*, *27*(23), 3829–3832, doi:10.1029/2000GL003827.
Stenbaek-Nielsen, H. C., M. G. McHarg, T. Kanmae, and D. D. Sentman (2007), Observed emission rates in sprite streamer heads, *Geophys. Res. Lett.*, *34*, L11105, doi:10.1029/2007GL029881.
van der Velde, O. A., Á. Mika, S. Soula, C. Haldoupis, T. Neubert, and U. S. Inan (2006), Observations of the relationship between sprite morphology and in-cloud lightning processes, *J. Geophys. Res.*, *111*, D15203, doi:10.1029/2005JD006879.
van der Velde, O. A., J. Montanyà, S. Soula, N. Pineda, and O. Chanrion (2009), Temporal and spatial evolution of intracloud lightning associated with sprite-producing positive cloud-to-ground flashes in northeastern Spain, paper presented at Chapman Conference on Effects of Thunderstorms and Lightning in the Upper Atmosphere, AGU, University Park, Pa.

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