Elves: Lightning-induced transient luminous events in the lower ionosphere

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Abstract. Observations of optical phenomena at high altitude above thunderstorms using a multichannel high-speed photometer and image intensified CCD cameras were carried out at Yucca Ridge Field Station (40°40' N, 104°56' W), Colorado as part of the SPRiTES'95 campaign from 15 June to August 6, 1995. These new measurements indicate that diffuse optical flashes with a duration of <1 ms and a horizontal scale of ~100-300 km occur at 75-105 km altitude in the lower ionosphere just after the onset of cloud-to-ground lightning discharges, but preceding the onset of sprites. Here we designate these events as 'elves' to distinguish them from 'red sprites'. This finding is consistent with the production of diffuse optical emissions due to the heating of the lower ionosphere by electromagnetic pulses generated by lightning discharges as suggested by several authors.

Introduction

Several earlier experiments observed transient luminosity increases over the night sky using photometers, most of which can be grouped as short (~1 ms time constant) and long (~20 ms duration) events [Ogulman, 1973; Nemzek and Winckler, 1989; Winckler et al., 1993]. Perhaps, Fast Atmospheric Pulsations with a 0.4 ms rise time and a 0.6 ms decay (as reported by Ogulman [1973]) are examples of short events. The source of the short events, always coincident with sprites, was speculated to be Rayleigh scattered distant lightning, whereas cloud-to-stratosphere or cloud-to-ionosphere lightning was proposed as a possible source of the long events [Winckler et al., 1993, 1995]. Coordinated imaging observations carried out from the ground and aircraft have revealed the existence of large luminous structures, now called sprites and blue jets using low-light-level SIT cameras [Franz et al., 1990; Sentman and Wescott, 1993; Sentman et al., 1995; Wescott et al., 1995] or image intensified CCD cameras [Lyons et al., 1984]. These phenomena were also observed from the Space Shuttle [Boeck et al., 1992, 1995; Vaughan et al., 1992]. Sprites occur singly or more typically in clusters of two or more, with vertical and horizontal extent of 5-30 km and 10-50 km, respectively and terminal heights of 90-100 km [Sentman et al., 1995]. Observations with an intensified color camera and an imaging spectrometer demonstrated that sprites are predominantly red [Sentman et al., 1995; Mende et al., 1995]. Another important character of sprites is that sprites are induced mostly by positive cloud-to-ground discharges [Boccippio et al., 1995]. Sprites can often occur as a whole within a single 17 ms field of video. Thus, we can not determine the region of initiation and the motions of sprites from video image data, although such information is essential to investigate the generation mechanism of sprites. In the SPRiTES'95 campaign carried out at Yucca Ridge Field Station, Colorado, we have simultaneously operated a multichannel high-speed photometer and image intensified CCD cameras to investigate the motions of sprites within one video field. From the obtained data, we have found that diffuse optical flashes with a duration of <1 ms occur at altitude 75-105 km in the lower ionosphere just after the onset of cloud-to-ground lightning discharges, but preceding the onset of sprites.

Observations

A high-speed (time resolution of 15 μs) photometer was used to simultaneously observe two different elevation angles (0.2° pointing accuracy) with a narrow field of view of 1.0° in the vertical direction and 9.5° in the horizontal direction. The photometer has four channels; one channel with a wide field of view is used for event triggering, while the remaining three channels with narrow fields of view are used to measure lightning flashes and associated high-altitude optical emissions. Photomultipliers with a broad response from 400 nm to 880 nm were used, occasionally with red filters (>640 nm) for one or two of the channels. The photometer outputs were sampled at intervals of 15 μs and 495 ms of data were recorded for each event on magneto-optical disk with the time code provided by a GPS system. The 495 ms data cover the time interval from 150 ms prior to the onset of elves or sprites to 345 ms after the onset.

Observations were carried out from Yucca Ridge Field Station (40°40' N, 104°56' W, 1670 m) of 20 km NE of Port Collins, Colorado as part of the SPRiTES'95 campaign from June 15 to August 6, 1995. In addition to the photometer, two sets of image intensified CCD cameras were operated to capture sprite images. One Xybion camera always had a 12.5 mm lens with a nominal horizontal field of view of 46 degrees. The second camera had a zoom lens, which could be varied from 46° to less than 10° field of view depending on the target. National Lightning Detection Network (NLDN) data was used to determine the locations of individual CG lightning flashes associated with sprite events. Due to their narrow (1°) vertical field of view, it was generally necessary to adjust the pointing (elevation and azimuth) of the photometers after the first sprite detection, taking advantage of the fact that sprites occurred repeatedly at intervals of several minutes, and generally in the same region of the sky.

A typical example of transient luminous events induced by lightning is shown in Figure 1. The location of a positive discharge (08:57:53.306 UT, +326 kA) coincident

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The difference in luminosity variations at 15° and 9° elevation angles can be interpreted by comparing the photometer data with the CCD camera image. Hence, successive images taken at 1/60 s (≈ 17 ms) intervals, with the image representing the luminosity integrated over a 17 ms interval. With respect to Figure 1, the time intervals covered by the three images are 301-318, 318-335, and 335-351 milliseconds. A diffuse flash with a bright core appeared suddenly (Figure 2a). In the next instance, only the diffuse flash surrounding the core disappeared (Figure 2b). The core is identified to be a sprite event since it has a vertical filament structure characterizing sprites. The luminosity of the core sprite subsequently decayed gradually, and a new sprite appeared to the left of the initial sprites (Figure 2c).

The fields of view of the photometer at elevation angles 15° and 9° are schematically illustrated in Figure 2d, and lie respectively inside and outside of the luminous region. By comparing Figures 1 and 2, we see that the initial short burst and the following long event in Figure 1 correspond respectively to the large-scale diffuse flash and the small-scale sprites in Figure 2. The simultaneous occurrence of both the diffuse flash and the bright core in Figure 2a is due to the 17 ms integration time.

The time delay from the initial diffuse flash to the onset of the following sprite event is found to be 7 ms in Figure 1. However, in different cases observed, this time delay ranged from several to several tens of milliseconds. Occasionally, only the diffuse flashes occurred. Also, sprites occurred frequently without the diffuse flashes. These characteristics suggest that the diffuse flashes with < 1 ms duration and the sprites are independent phenomena. Here we tentatively designate the diffuse flash events as “elves”, an acronym for Emissions of Light and VLF perturbations due to EMP Sources, since the most likely source of these lower ionospheric flashes appears to be the heating of lower ionospheric electrons by the electromagnetic pulse generated by lightning discharge, as discussed later. The ELF/VLF radio atmospheric signatures of lightning flashes associated with elves and sprites were investigated by Reising et al. [1995] and Takahashi et al. [1995]. It was found that elves were always accompanied by large-amplitude VLF perturbations.

During the period from June 23 to July 8, 1995, 35 lightning-induced transient luminous events were observed with the photometer and the CCD cameras. Of these, elves were detectable in 18 events (3 cases for elves without sprites and 15 cases for elves with sprites). In the remaining 17 cases, sprites occurred without elves. Typical examples of elves at distances of ~ 200 km from Yucca Ridge are shown in Figure 3. It is apparent that the vertical extent of the luminous layer is fairly narrow, ranging in these cases from ~ 75 to ~ 100 km altitude.

The altitudes of the luminous regions on the CCD images can be estimated by assuming that the core of the luminous region is located immediately above the associated positive discharge identified by NLDN. The altitude range and the horizontal dimension of the diffuse luminous region for the distant elves were estimated to be 75-105 km and 100-300 km, respectively, while those of the cluster of sprites in the central core were thus estimated to be 65-90 km and 10-50 km, respectively. The altitude range of sprites was based on the elevation angles at the top and bottom of the vertically aligned filaments. Further, the luminous layer of elves was observed to move downward with a speed of about one tenth to one third of the light speed. The downward motion in the case of Figure 3 is shown in Figure 4. Additional evidence concerning the vertical motions of the elves and sprites was presented by Takahashi et al. [1995].

**Discussions**

Rayleigh scattered distant lightning has been suggested as a possible source of previously observed transient luminosity increases [Nemzek and Winckler, 1989; Winckler et al., 1993]. Such scattering may have contributed to the first
Figure 2. CCD camera images during the transient luminous event given in Figure 1. Three successive images taken at 17 ms intervals are shown in (a)-(c), while the fields of view of the photometer are shown in (d). A narrow dark band seen inside the luminous region is a patch of clouds.

Figure 3. Example of lightning-induced diffuse flashes (tentatively called elves) in the lower ionosphere. This event occurred at a distance of 537 km from the observation point, Yucca Ridge Field Station.

Figure 4. Traces of photometer signals for the June 25, 1995 event given in Figure 3. The photometer channels with elevation angles of 6.7° and 4.6° point the upper and bottom parts of the emission layer, respectively as shown by two arrows at the right side of Figure 3.
peak in the double peak structure in Figure 1b, since the luminosity was simultaneously observed in both the high and low elevation channels, and coincident with VLF sferics. However, the altitude dependence expected for Rayleigh scattering such as being brighter at lower elevation angle is not seen in the first peak. This inconsistency appears to be due to the screening effect of near clouds, since a patch of clouds was observed within the field of view of the $15^\circ$ elevation channel, but such a patch was not observed within the field of view of the $15^\circ$ elevation channel.

The second peak identified as elves can not be attributed to Rayleigh scattered distant lightning, since it is seen only in the high elevation channel, and corresponds to the bright, diffuse flash at 75-105 km altitude. Also, such signatures were not observed in literally thousand of CCD images of bright cloud illuminations. Elves appear to occur in response to some especially energetic +CG flashes. Of 35 elves/spires, 32 events were associated with CGs detected by the LNLN. In these 32 events, only one event (elves with sprites at 06: 00: 49.095 UT on 4 July 1995) was associated with a large negative polarity flash (-131 kamp) and the remaining 31 events were associated with +CGs. The magnitude of CGs in the cases of elves only or elves with sprites is much higher than sprites only (148 kamp versus 63 kamp in this sample). The same tendency was reported by Lyons et al. [1996] using different sample obtained on July 24, 1995 during the SPRITE'S95 campaign period.

The most likely source of elves is heating of the lower ionospheric electrons by the electromagnetic pulse (EMP) generated by the intense lightning discharge as has been previously suggested [Inan et al., 1991; Taranenko et al., 1992, 1993]. The observed time delay of 350 μs from the onset of the first peak to the onset of the second peak in Figure 1 is interpreted by a model that the EMP propagation is upward and it takes this time to reach the lower ionospheric altitudes of 75-105 km. A quasi-static electric field model proposed for sprite events by Pasco et al. [1995] may be an additional source for elves, since the observed rapid downward shift of the luminous layer is consistent with the model. However, none of the models proposed for sprites so far can explain the delayed occurrence and long duration of sprites. Elves induced in the lower ionosphere by lightning discharges have a horizontal scale much larger than that of sprites. On the other hand, both the horizontal extent and narrow altitude extent of elves are similar to those of the lightning associated airglow brightening observed from the Space Shuttle [Boeck et al., 1995]. The observed high luminosity, typically 1-10 MR, suggests that the lower ionosphere is heated significantly during these events, as has been predicted by Taranenko et al. [1993]. Thus, elves may have a significant effect on the lower ionosphere and on radio wave propagation.

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