Lightning parameters of sprites and diameter of halos

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Abstract

Transient Luminous Events (TLEs) above thunderclouds have been associated with variables such as the lightning Charge Moment Change (CMC), charge height, charge transfer, and rise-time. We show for the first time a survey of the CMC, rise-time, fall-time, peak electric field, and peak current of the lightning discharges associated with 11 column, 11 carrot, and 18 sprites with halo. We found that carrot sprites are induced by a lightning discharge with CMC, peak electric field, and peak current greater and less than that for column sprites and sprites with halo, respectively. Sprites with a halo are initiated by a lightning discharge with a longer rise-time and fall-time than that for column and carrot sprites. Column sprites top altitude and carrot sprites brightest region altitude positively correlate with lightning rise-time. Lightning fall-time, peak electric field, and peak current increase with a decrease in the top and brightest region altitudes for carrot sprites. For the altitude of the sprites brightest region, column sprites correlate negatively with lightning fall-time, peak electric field, and CMC, and column sprites top altitude also correlates negatively with lightning peak electric field. Sprites with a halo top altitude increased with lightning fall-time and peak current, and sprites with a halo brightest altitude increased with an increase in lightning CMC. Halo diameters correlate positively with lightning fall-time, peak electric field, and peak current.

Keywords: Lightning rise-time; lightning fall-time; lightning Charge Moment Change; Lightning electric field; Lightning current; Transient Luminous Events altitude

1. Introduction

Sprites are vertically oriented luminous electric discharges induced by the cloud-to-ground (CG) lightning quasi-static electric field and continuing current. They appear at stratospheric and mesospheric altitudes of about 40 to 100 km (Füllekrug et al., 2006; Liu et al., 2015; Pasko, 2010; Pasko et al., 2013; Siingh et al., 2012; Surkov and Hayakawa, 2020). In contrast, halos manifest as a horizontal disc of luminous emission, also generated by the CG lightning quasi-static electric field and continuing current, at ionospheric altitudes of about 85 km. The duration of the electric field at a certain altitude is almost equivalent to the local Maxwellian relaxation time, which is defined as the permittivity of free space over the local conductivity. The local Maxwellian relaxation time increases with a decrease in atmospheric altitude (Liu et al., 2015; Pasko et al., 1997).

Sprites and halos may be induced by mainly positive CG lightning electric fields, although some are generated by negative CG lightning discharge. Sprite streamers tend to develop from halos (Luque & Ebert, 2009). Column sprites are associated with only the downwards propagation of streamers, whereas carrot sprites are associated with both downwards and upwards streamer propagation (Bór, 2013). The Transient Luminous Events (TLE) manifest themselves about 1—100 ms after the parent CG lightning flash. (Bering et al., 2004; Chen et al., 2019; Frey et al., 2007; Liu et al., 2015; McHarg et al., 2002; Siingh et al., 2012; Williams et al., 2012). The parent lightning waveforms are shorter than the duration of the TLE luminosity.

Parameters such as lightning charge height, charge transfer, rise-time, and Charge Moment Change (CMC) are essential in determining whether the lightning stroke initiates sprites or halos (Asano et al., 2008; Yaniv et al., 2014; Haspel et al., 2020; Li et al., 2008; Mashao et al., 2021). Lightning with a mean and minimum CMC value of approximately 1480 C-km and 63 C-km has been associated with the generation of sprites (Chen et al., 2019). Enhancement in sprites brightness with an increase in lightning CMC has been reported by Yaniv et al. (2014), Yang et al. (2017), and Nnadih et al. (2018). Mashao et al. (2021) demonstrated a positive correlation between lightning CMC and sprites top altitude. The importance of lightning rise-time on sprites has been established by Asano et al. (2008) using a two-dimensional computer simulation for summer and winter storm conditions. According to Asano et al. (2008), lightning charge height, charge transfer, and rise-time are essential in the generation and development of sprites. The sprites breakdown region reduces in altitude for a longer rise-time (>25 µs) (Asano et al., 2008). We are not aware of any reported lightning fall-time regarding TLEs.

The altitudes of sprites have been well established using different techniques and high-speed cameras. The sprites top altitude has been observed to vary from 73 to 96 km, whereas the altitude of the sprites brightest region has been found to span from 50 to 84.1 km (Füllekrug et al., 2019; Luque et al., 2016; Mashao et al., 2021 Malagón-Romero et al., 2020; Sentman et al.,1995; Stenbaek-Nielsen et al., 2010; Wescott et al., 1998). Mashao et al. (2021) found that the average sprites top altitude in South Africa occurred at approximately 84.3 km. Other authors found sprite top altitudes at 88 km (Sentman et al., 1995), 86.4 km (Wescott et al., 1998), and 79-96 km (Stenbaek-Nielsen et al., 2010). Mashao et al. (2021) found that the average altitude of maximum brightness in South Africa occurred at approximately 69 km. Other authors found the altitude of maximum brightness at 70 km (Malagon-Romero et al., 2020) and 71.2-72.4 km (Luque et al., 2016). Wescott et al. (2001) observed that the top altitude of sprites with halos varied from 73.5 km to 85.2 km, with an apparent diameter of about 66 km. Taylor et al. (2008) found a diameter of about 89± 5 km for a negative CG sprite with a halo. According to Miyasato et al. (2002), the average halo diameter was about 86 km.

In this paper, we demonstrate for the first time the importance of lightning CMC, peak electric field, peak current, rise-time, and fall-time on sprites altitude and halo diameters for different sprites morphologies. This is done by evaluating the linear correlation between lightning CMC, peak electric field, peak current, rise-time, and fall-time versus the top altitude and altitude of the brightest region of column sprites, carrot sprites, and any sprites with halos. In addition, we measure the diameter of halos in South Africa for the first time.

2. Observations

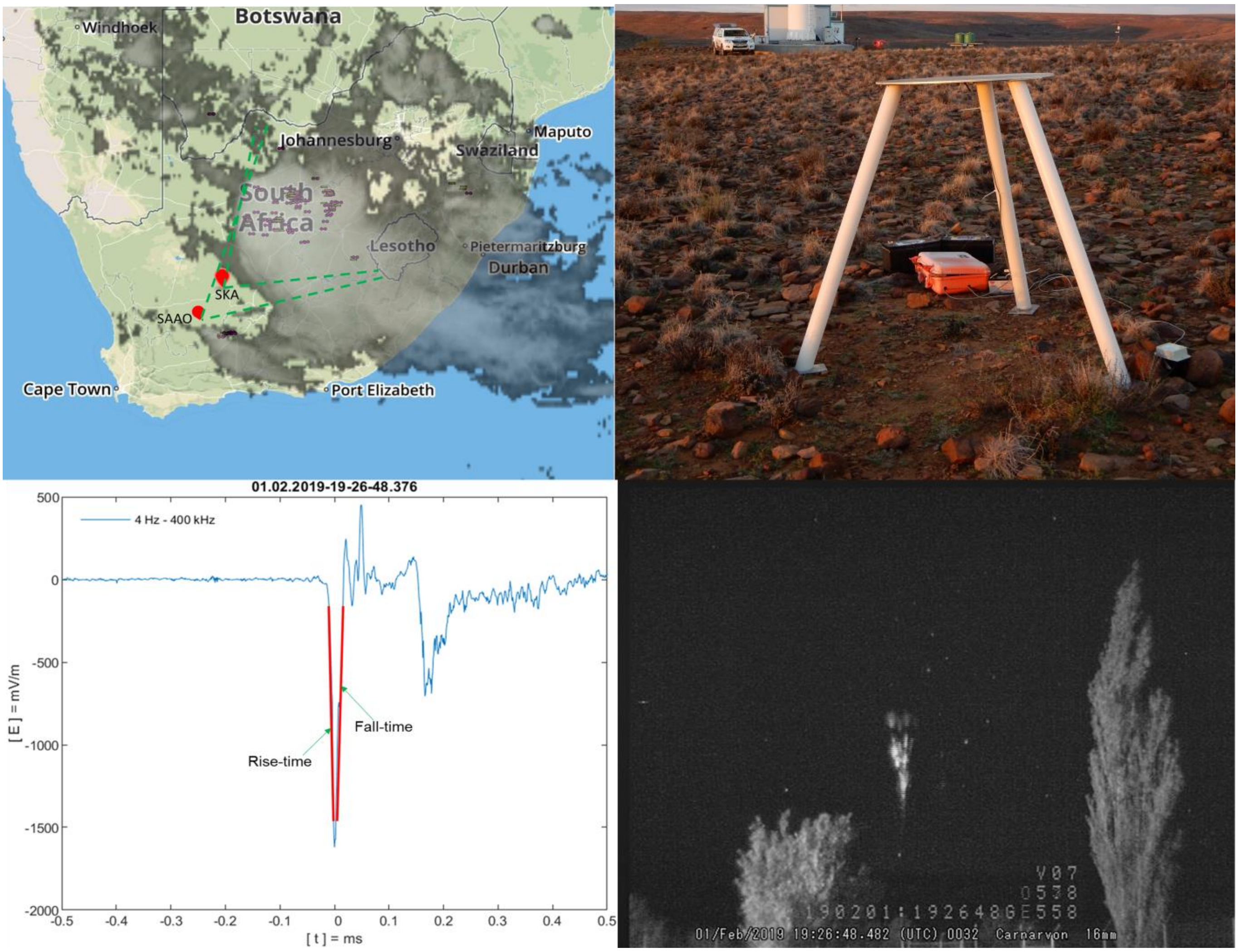

Fig. 1. South African map (top left panel, obtained from EarthNetworks) denoting the thunderstorm which initiated some of the TLEs in this paper and observation sites (red dots) of the South African Astronomical Observatory (SAAO) and Square Kilometre Array (SKA) in the Northern Cape, South Africa. The green dotted lines show camera viewing directions. The yellow plus, yellow negative, and pink dash-like symbols denote the positive CG, negative CG, and intracloud lightning, respectively. Lightning vertical electric field (bottom left panel) associated with a carrot sprite (bottom right panel) measured by the ELF receiver (4 Hz- 400 kHz) (top right panel). The red lines (bottom left panel) indicate where the rise-time and fall-time were calculated from 90% to 10% of the maximum electric field signal deflection from the background. A carrot sprite recorded on 01 February 2019 at 19:26:48.558 UTC (bottom right panel) using a Watec 910Hx camera.

2.1 Camera systems

The 2019 sprites campaign was conducted from 28 January to 15 February 2019. Out of about 208 TLEs, 40 TLEs consisting of 11 column, 11 carrot, and 18 sprites with halos were selected for our analysis. The TLEs presented here were recorded using Watec 910Hx cameras (Bór, 2013; Gamerota et al., 2011; Liu et al., 2016; Soula et al., 2009; Stenbaek-

Nielsen et al., 2010; Yaniv et al., 2014). We selected the TLEs that only contain column, carrot, and sprites with a halo to make a fair parent lightning parameters comparison. However, sprites with a halo consist of column, carrot, wishbone, and jellyfish sprites. Fig. 1 (top left panel) shows two distinct locations; the Square Kilometre Array (SKA) (30.97º S, 21.98º E) and the South African Astronomical Observatory (SAAO) (32.38º S, 20.81º E), where the Watec 910Hx cameras were operated. Both locations are in the Karroo desert of the Northern Cape of South Africa, see Fig. 1 (top left panel). Several Mesoscale Convection Systems (MCS) initiated the TLEs, moving from the northwest to the southeast over South Africa on 29 and 30 January as well as 1, 2, and 11 February 2019. The MCS produce TLEs for about 4 hours on average each night. Fig. 1 (top left panel) shows one MCS that induced the observed TLEs events (https://www.earthnetworks.com/product/decision-support-collaboration-tools/sferic-maps/). The 40 TLEs presented here were recorded on 29, 30 January and 11 February 2019 from SAAO and 1 and 2 February 2019 from SKA. Fig. 1 (bottom right panel) shows an example carrot sprite observed from SKA on 1 February 2019.

The Watec 910Hx cameras had a 8.0 mm f/1.4 C-mount lens, giving a field of view (FOV) of 46.2º horizontal and 29º vertical. The Watec 910Hx cameras operated under fixed gain and a gamma factor of 0.45. The observation systems recorded sprites video clips at 25 fps with a 40 ms frame period. A GPS video timer installed in one camera system provided millisecond timing. A Network Timing Protocol server provided timing accuracy of about 1 ms for the other camera systems at SKA and SAAO. The camera systems operated with 8-bit intensity resolution. The video images had a size of 640x480 pixels with an angular resolution of 0.072º horizontal and 0.061º vertical per pixel. Thus, 1 pixel is 0.061º in elevation angle.

2.2 Altitude estimation

The stars in the sprites image background allowed us to determine the azimuth and elevation angle of every pixel. The stars declination and right ascension from the star almanac, event time, and observation site were used to fit the modeled stars onto the real stars in the sprites image background in order to find the camera pointing direction and FOV, and to determine the azimuth and elevation angle of each pixel. To estimate the altitude of sprites, we assumed that sprites were induced directly above their parent CG lightning strokes. This supposition is usually used in TLEs studies (Füllekrug et al., 2019; Li et al., 2008; Luque et al., 2016; Mashao et al., 2021; McHarg et al., 2007). The sprites altitude was estimated from their elevation angle and ground distance from the observation location. This was done by employing planar trigonometry in the vertical plane and spherical trigonometry in the horizontal plane. The method is fully described in Mashao et al. (2021). The altitude of sprites uncertainty, which depends on the slant distance between observation location and targeted sprites altitude, spanned ±0.33-0.47 km.

The sprites altitudes were estimated for two regions: the top altitude and the altitude of the brightest region. For a vertical profile through each TLE, the top altitude is the highest elevation angle pixel with an intensity value greater than the background. The diameter of the halos is determined in the same way for a horizontal profile. The altitude of maximum brightest is taken from the pixel of greatest intensity value within the TLE. The sprite top altitude is where electric field energy within a sprite is normally less than the altitude dependent critical breakdown field. The brightest region is where photon production maximizes due to collisions between the accelerated electrons and background neutrals (Liu et al., 2015; Mashao et al., 2021).

2.3 Lightning detection

We obtained the lightning information (time, position, peak current) of the TLEs parent CG lightning strokes from the South African Weather Service (SAWS) and Earth Networks (EN) (Gijben, 2012; Zhu et al., 2017). The parent CG lightning strokes were located between 242 and 707.5 km away from the observation sites, so well within the maximum observing range (900 km). The parent lightning strokes were all of the positive polarity with a peak current spanning from 32 to 179 kA. Based on timing data, SAWS and EN did not detect all lightning discharges which initiated the TLEs. This limited the number of TLEs to report.

2.4 Electromagnetic Waveforms

A wideband digital ELF radio receiver, co-located with the cameras, detected the lightning vertical electric field strength associated with the optical sprites in the frequency ranging from ~4 Hz to ~400 kHz with a sampling frequency of 1 MHz and timing accuracy of 12 ns (see Fig. 1, top right panel) (Füllekrug, 2010). The ELF radio receiver was positioned in a low radio interference area near the SKA site. The TLEs parent lightning electric field strength span 1.0-3.8 V/m at the ELF radio receiver location. The lightning rise-time and fall-time were computed from the vertical electric field measured simultaneously with the optical observations (Füllekrug, 2010; Füllekrug et al., 2019). The rise-time calculations were from 90% to 10% of the maximum electric field signal deflection from background. The same method was applied to the fall-time (see Fig. 1, bottom left panel).

The lightning CMC values ranged from 689 to 6,780 C-km and were computed from the far-field magnetic field data recorded by a broadband ELF system installed in the Bieszczady mountains in Poland (49.20º N, 22.54º E), using the method described by Mlynarczyk et al. (2015). The ELF system measures the two horizontal magnetic field components in the frequency range from 0.01 to 1,000 Hz with a sampling frequency of 3 kHz (Mlynarczyk et al., 2018). Due to signal noise and unknown locations of the parent lightning strokes, we could compute the lightning CMC for 31 TLEs, see Table 1 in the appendix.

All data are summarized in Table 1 in the appendix.

3. Results and discussions

An analysis of lightning rise-time, fall-time, peak electric field, peak current, and CMC associated with TLEs was conducted on 11 column sprites, 11 carrot sprites, and 18 any sprites with halos. Note that the sprites with halos have different morphologies, i.e., column, carrot, wishbone, and jellyfish. The lightning electric radiated fields propagate as $^{1}/_{r^2}$, where *r* is the distance from the lightning location to the receiver location (Cooray and Lobato, 2020). For comparison, we normalized the lightning peak electric field values for the distance from the ELF receiver to the lightning stroke location. This was done by multiplying the lightning peak electric field values by the distance squared (in km) relative to 1 km (Taylor and Jean, 1959).

The lightning normalized peak electric field, peak current, rise-time, fall-time, and CMC associated with the analyzed TLEs vary from 93 to 914 kV/m, 32 to 179 kA, 6 to 25 µs, 1 to 91 µs, and 689 to 6,780 C-km, respectively. Most of the investigated TLEs producing parent lightning had a very short rise-time (<15 µs) and short fall-time (<25 µs); see Table 1. We found that TLEs top altitudes vary from 71 to 90.5 km, with an average and standard deviation of 79.8 and 5.2 km, respectively. The TLEs top altitudes are in the altitude range previously reported in the literature (Füllekrug et al., 2019; Luque et al., 2016; Mashao et al., 2021 Malagón-Romero et al., 2020; Sentman et al.,1995; Stenbaek-Nielsen et al., 2010; Wescott et al., 1998). The analyzed TLEs brightest region altitude ranged from 50 to 73 km, with an average and standard deviation of 61.5 and 6.4 km, respectively. The TLEs altitude of maximum brightness are in the altitude range reported in the literature (Füllekrug et al., 2019; Luque et al., 2016; Mashao et al., 2021 Malagón-Romero et al., 2020; Sentman et al.,1995; Stenbaek-Nielsen et al., 2010; Wescott et al., 1998).

The top altitude for column sprites, carrot sprites, and sprites with halos (halo top) varied from 72.4 to 86.4 km, 70.7 to 87 km, and 71.5 to 90.5 km, respectively. We obtained an average top altitude for column sprites, carrot sprites, and sprites with halos of about 80.4, 80.6, and 78.9 km, with the standard deviation of about 4.6, 5.1, and 5.6 km, respectively. The brightest region altitude for column sprites, carrot sprites, and sprites with halos ranged from 55.1 to 73 km, 50 to 68.5 km, and 50 to 68 km, respectively. The average altitude for column, carrot, and sprites with halos was 66 (6.5), 61 (5.5), and 59 (5.2) km, where the value in parenthesis is the standard deviation.

The lightning peak electric field, peak current, CMC, rise-time, and fall-time for column sprites ranged from 101 to 355 kV/m, 34 to 87 kA, 880 to 2,410 C-km, 7 to 16 µs, and 1 to 30 µs, respectively, with an average of 211 (74) kV/m, 48.5 (15.2) kA, 1,674 (583) C-km, 11.1 (2.8) µs, and 15.3 (8.1) µs, where the value in parentheses is the standard deviation. Carrot sprites were induced by lightning flashes with peak electric field, peak current, CMC, rise-time, and fall-time varying from 93 to 427 kV/m, 32 to 92 kA, 1,360 to 3,060 C-km, 6 to 19 µs, and 1 to 32 µs, respectively, with an average of 233 (125) kV/m, 58 (17.4) kA, 2,187 (601) C-km, 11 (5) µs, and 15.6 (12.2) µs. The lightning peak electric field, peak current, CMC, rise-time, and fall-time, which initiated any sprites with halos, had values ranging from 180 to 914 kV/m, 60 to 179 kA, 639 to 6,780 C-km, 8 to 25 µs, and from 10 to 91 µs, respectively, with an average of 519 (210) kV/m, 106.2 (30.6) kA, 2,909 (1,983) C-km, 12.8 (4.8) µs, and 36.3 (22.4) µs.

Clearly, column and carrot sprites require a less lightning CMC and smaller lightning rise-time and fall-time compared to any sprites with a halo. Sprites with halos require a significantly greater lightning CMC and significantly longer lightning fall-time when compared to carrot and column sprites, as shown in Table 1. Column sprites require a lower lightning electric field and peak current compared to carrot sprites and sprites with a halo. The lightning discharges which initiate carrot sprites have a CMC, peak electric field, and peak current greater and less than that of the column sprites and sprites with halo, respectively.

We correlated the various lightning parameters against the brightest region and top altitude of column, carrot, and sprites with halo, and their relationships are presented below. According to Peat et al. (2009), Pearson’s linear correlation coefficients spanning from 0.1 to 0.3 are small correlations, 0.3 to 0.5 are moderate correlations, and greater than 0.5 are high correlations.

3.1 Sprites top altitude

Fig. 2 shows the relationship between lightning fall-time (X, µs) (top left row), normalized peak electric field (E, kV/m) (top middle row), and peak current (I, kA) (top right row) versus the top altitude (Y, km) of carrot sprites. Fig. 2 also shows lightning rise-time (T, µs) (middle left row) and normalized peak electric field (E, kV/m) (middle center row) versus the top altitude (Y, km) of column sprites, as well as lightning fall-time (X, µs) (bottom left row) and peak current (I, kA) (bottom right row) versus top altitude (Y, km) of sprites with a halo. The Pearson correlation coefficient (r) and the linear fit equation (Y, km) are denoted on the top corner of each panel. The weak correlations are insignificant and therefore not presented.

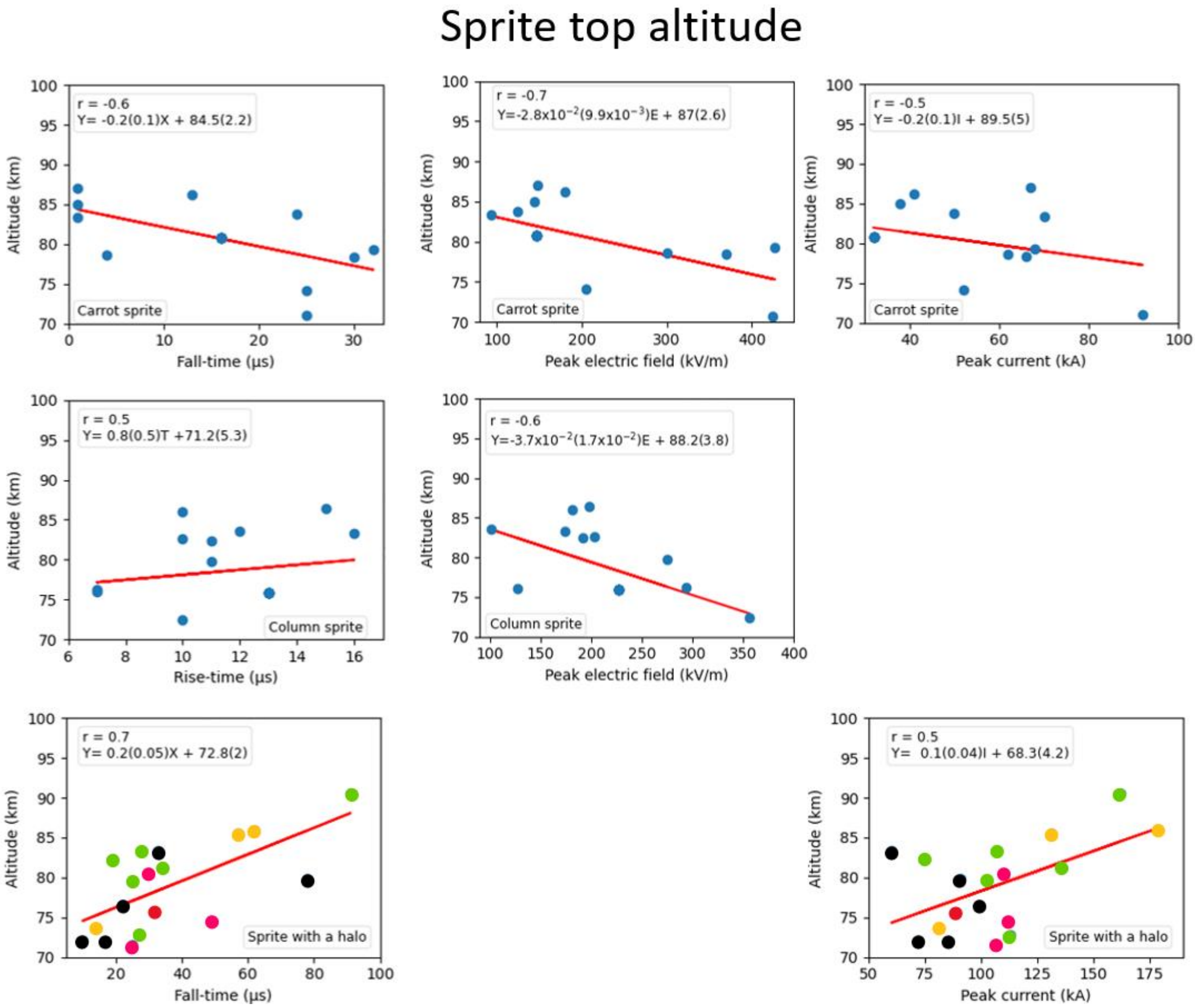

Fig. 2. Lightning fall-time (X, µs) (top left row), normalized peak electric field (E, kV/m) (top middle row), and peak current (I, kA) (top right row) versus the top altitude (Y, km) of carrot sprites. Lightning rise-time (T, µs) (middle left row) and normalized peak electric field (E, kV/m) (middle center row) versus the top altitude (Y,

km) of column sprites. Lightning fall-time (X, μs) (bottom left row) and peak current (I, kA) (bottom right row) versus top altitude (Y, km) of sprites with a halo. Green, purple, red, yellow, and black dots on the sprite with a halo plot shows column, carrot, wishbone, jellyfish, and “column and carrot” sprites, respectively. The Pearson correlation coefficient (r) and the linear fit equation (Y, km) are denoted on the top corner of each panel. The value in parentheses in the linear fit equation is the uncertainty.

The top altitude of column sprites against lightning rise-time and peak electric field showed good positive and negative linear correlations (0.5) and (-0.6), respectively. The good positive (0.5) and weak negative (-0.2) (not shown) correlations found between the lightning rise-time and fall-time against the top altitude of column sprites, respectively, might be associated with the downward propagation of streamers and the lack of upward propagating streamers during column sprites initiation processes (Bór, 2013).

The top altitude of carrot sprites against lightning fall-time, peak electric field, and peak current showed good negative linear correlations (-0.6), (-0.7), and (-0.5), respectively. The top altitude of sprites with halos against lightning fall-time and peak current showed good positive linear correlations (0.7) and (0.5), respectively. For carrot sprites, this suggests that the electrical breakdown region decreases in altitude for a longer fall-time, greater peak electric field, and greater peak current.

3.2 Sprites brightest region altitude

Fig. 3 shows the relationship between lightning fall-time (X, μs) (top left row), normalized peak electric field (E, kV/m) (top middle row), and CMC (Z, C-km) (top right row) versus the altitude (Y, km) of the brightest region for column sprites. Fig. 3 also shows lightning rise-time (T, μs) (middle left row), normalized peak electric field (E, kV/m) (middle center row), fall-time (X, μs) (bottom left row), and peak current (I, kA) (bottom center row) versus the altitude (Y, km) of the brightest region for carrot sprites (middle row), as well as lightning CMC (Z, C-km) (bottom right row) versus the altitude (Y, km) of the brightest region for sprites with a halo (bottom row). The Pearson correlation coefficient (r) and the linear fit equation (Y, km) are denoted on the top corner of each panel.

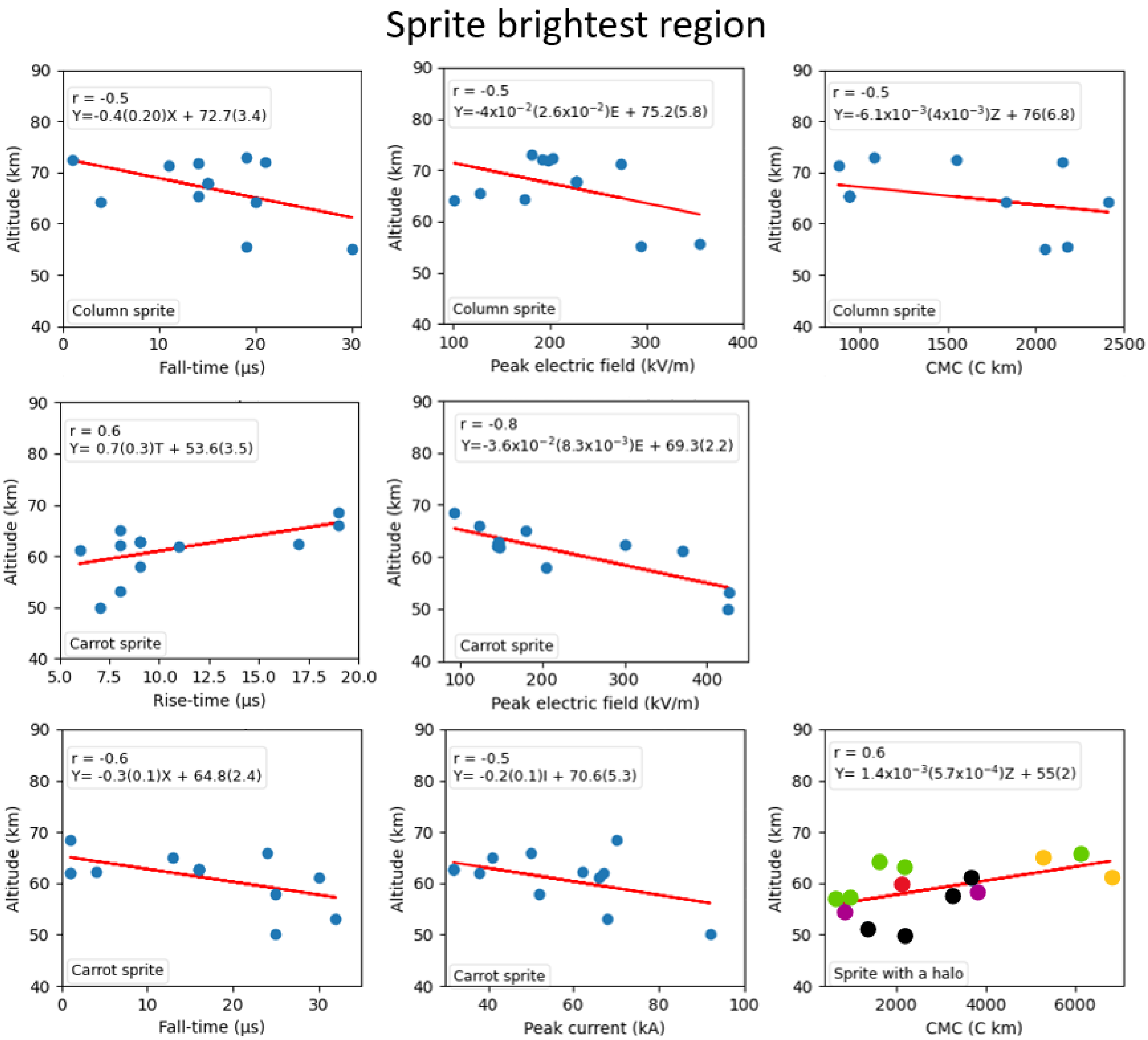

Fig. 3. Lightning fall-time (X, µs) (top left row), normalized peak electric field (E, kV/m) (top middle row), and CMC (Z, C-km) (top right row) versus the altitude (Y, km) of the brightest region for column sprites. Lightning rise-time (T, µs) (middle left row), normalized peak electric field (E, kV/m) (middle center row), fall-time (X, µs) (bottom left row), and peak current (I, kA) (bottom center row) versus the altitude (Y, km) of the brightest region for carrot sprites (middle and bottom row). Lightning CMC (Z, C-km) (bottom right row) versus the altitude (Y, km) of the brightest region for sprites with a halo (bottom right row). Green, purple, red, yellow, and black dots on the sprite with a halo plot show column, carrot, wishbone, jellyfish, and “column and carrot” sprites, respectively. The Pearson correlation coefficient (r) and the linear fit equation (Y, km) are denoted on the top corner of each panel. The value in parentheses in the linear fit equation is the uncertainty.

For column sprites, there are good negative correlations for the altitude of maximum brightness versus lightning fall-time (-0.5), peak electric field (-0.5), and CMC (-0.5). The altitude of maximum brightness for carrot sprites shows a good positive correlation against lightning rise-time (0.6) and a good negative correlation against lightning peak electric field (-0.8), peak current (-0.5), and fall-time (-0.6). The good positive and negative correlation for carrot sprites against lightning rise-time and fall-time, respectively, might be related to the downward and upward propagation of streamers during carrot sprites initiation (Bór, 2013). On the other hand, for any sprites with halos, the altitude of maximum brightness has a good positive correlation with lightning CMC (0.6).

The results indicate that lightning with a longer fall-time, larger electric field, larger peak current, and larger CMC tend to deposit more energy at lower altitudes for column and carrot sprites, as shown in Fig. 3. However, lightning with larger CMC tends to deposit more energy at higher altitudes for sprites with a halo.

3.3 Sprites with a halo diameter

Fig. 4 shows the relationship between lightning fall-time (X, μs) (top panel), normalized peak electric field (E, kV/m) (middle panel), and peak current (I, kA) (bottom panel) versus halo diameters (W, km) for different types of sprites. The Pearson correlation coefficient (r) and the linear fit equation (W, km) are denoted on the top corner of each panel.

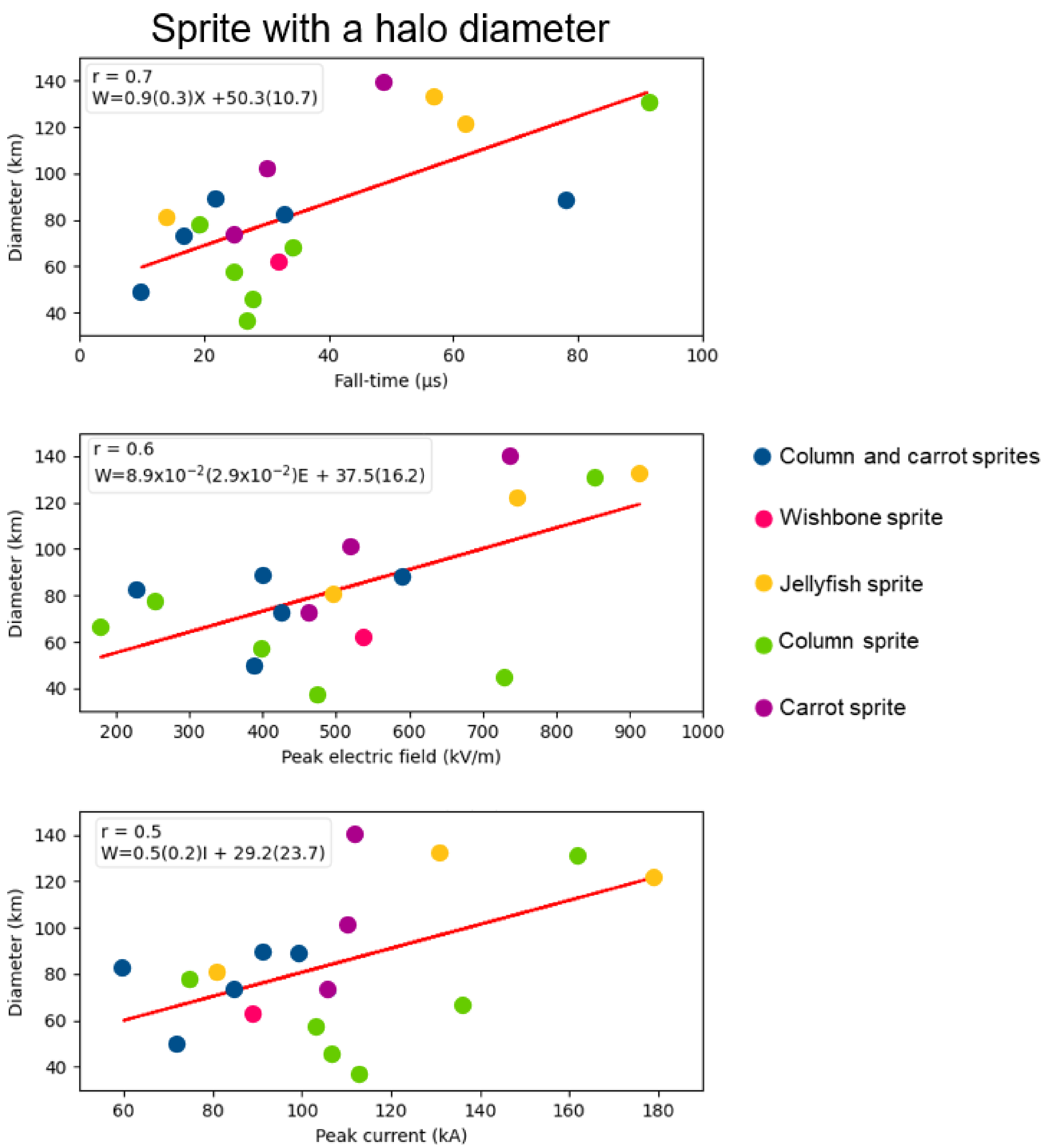

Fig. 4. Lightning fall-time (X, μs) (top panel), normalized peak electric field (E, kV/m) (middle panel), and peak current (I, kA) (bottom panel) versus halo diameters (W, km) for different types of sprites (color coded). Note that the "column and carrot sprites" are where both types occur together. The Pearson correlation coefficient (r) and the linear fit equation (W, km) are denoted on the top corner of each panel. The value in parentheses in the linear fit equation is the uncertainty.

We found that halo diameters span between 37 and 140 km with an average of 84 (31) km, where the standard deviation is given in parentheses. A correlation coefficient of 0.7 exists between lightning fall-time and halo diameter, and a correlation coefficient of 0.6 exists between normalized lightning peak electric field and halo diameter. The lightning peak current and halo diameter show a good correlation (0.5), see Fig. 4. In all cases, the larger the lightning peak electric field, peak current, and fall-time, the larger the halo diameters.

A decrease in lightning parameter with altitude follows the behaviour of the electric field and Maxwellian relaxation time in the Earth's atmosphere (Liu et al., 2015). It is known that the lightning CMC magnitude also depends on the duration of the continuing current. Thus, a longer continuing current enhances the lightning CMC magnitude estimate. The results suggest that the larger lightning CMC and fall-time are capable of sustaining maximum photon production at a low altitude compared to small lightning CMC and fall-time. The lightning CMC, peak electric field, peak current, rise-time and fall-time are essential in the generation and development of TLEs or sprites morphologies.

The results show that the lightning rise-time, fall-time, CMC, peak current, and peak electric field are essential in determining whether the lightning discharge initiated the TLEs or what type of sprites morphologies were initiated. The lightning rise-time, which is not usually reported (Asano et al., 2008; Haspel et al., 2020) and lightning fall-time, which has not been reported in TLEs literature, should be included in the future lightning and TLEs studies.

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Data availability

On request from the author (s)

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Appendix

Table 1. Summary of column and carrot sprites and sprites with halos including time, date, CG lightning strokes position and lightning peak current as reported by SAWS and EN; distance from the ELF receiver to the lightning location; lightning electric fields, rise-times, and fall-times computed from the ELF data; lightning CMC enumerated from the broadband magnetic field recording in the Bieszczady Mountains (49.20º N. 22.54º E), Poland; and TLEs estimated top altitude and altitude of the brightest region. Different font color shows information related to sprites with halos (purple), column sprites (blue), and carrot sprites (black).

Time (UTC)	LAT (º)	LON (º)	Peak current (kA)	Distance from ELF receiver to lightning (km)	Electric Field at 1 km from lightning location (kV/m)	Rise-time (µs)	Fall-time (µs)	CMC (C-km)	TLEs top altitude (km)	TLEs altitude of brightest region (km)	Halo diameter (km)
2019-02-01 18:45:10.752	-29.24	25.35	113	376.8	475.0	10	27	6090	72.7	65.5	37
2019-02-01 19:43:09.728	-29.60	25.07	103	333.4	396.6	11	25	2150	79.5	63.0	57
2019-02-01 20:10:11.537	-28.78	25.86	89	445.9	539.6	12	32	2130	75.6	60.2	63
2019-02-01 20:14:00.121	-29.71	25.29	60	347.3	229.3	8	33	3240	83.3	58.0	82
2019-02-01 20:29:36.130	-28.57	25.14	110	404.9	518.9	11	30	3790	80.5	58.5	102
2019-02-01 21:05:14.339	-29.24	24.62	75	319.1	255.8	22	19	689	82.3	56.6	77
2019-02-01 21:05:14.439	-29.05	24.78	72	344.3	388.8	10	10	3683	72.1	60.7	50
2019-02-01 21:18:40.722	-28.55	25.61	179	441.6	748.9	15	62	5270	86.0	65.0	122
2019-02-01 21:54:07.906	-28.90	26.63	131	504.4	914.0	8	57	6780	85.5	61.3	133
2019-02-02 20:54:36.370	-31.04	27.04	91	483.4	401.6	13	78	1340	79.9	51.4	89
2019-02-02 21:11:55.386	-30.25	26.58	99	448.6	592.4	16	22	2170	76.6	50.0	89
2019-02-02 22:44:38.719	-31.77	27.19	162	502.3	853.4	18	91	930	90.5	57.1	131
2019-02-11 19:53:57.116	-28.24	26.41	112	707.5	737.8	10	49	840	74.6	55.0	140
2019-01-30 20:40:17.642	-29.29	23.65	136	241.9	179.5	9	34	1620	81.2	64.0	67
2019-02-11 19:46:46.836	-28.22	25.66	107	656.1	727.2	8	28		83.3	68.0	45
2019-02-01 20:19:35.061	-29.02	25.34	106	389.1	463.5	10	25		71.5	59.0	73
2019-02-02 22:06:00.242	-31.18	26.98	81	476.7	496.6	25	14		73.6	57.0	81
2019-02-02 21:06:16.417	-30.96	27.19	85	496.4	425.8	14	17		72.0	50.0	73
2019-02-01 19:05:21.584	-29.38	25.21	50	357.3	355.4	10	19	2180	72.4	55.6	
2019-02-02 21:53:21.111	-31.15	27.02	50	481.0	293.6	7	30	2050	76.2	55.1	
2019-01-29 19:39:29.981	-29.42	24.39	34	289.1	100.8	12	20	1830	83.5	64.2	
2019-01-29 20:49:49.668	-29.23	24.79	56	332.7	173.7	16	4	2410	83.3	64.3	

2019-01-29 22:48:06.932	-28.18	24.71	44	406.4	203.1	10	1	1550	82.6	72.4	
2019-01-29 23:03:02.432	-28.13	24.69	34	410.2	192.0	11	21	2150	82.4	72.0	
2019-01-29 23:10:49.261	-27.91	24.32	51	421.3	181.1	10	19	1080	86.0	73.0	
2019-01-30 21:19:28.474	-29.34	24.82	87	328.0	274.3	11	11	880	79.8	71.3	
2019-01-30 22:05:21.758	-28.97	24.73	37	345.8	126.8	7	14	940	76.0	65.4	
2019-01-29 23:00:17.969	-28.20	25.06	36	428.9	197.6	15	14		86.4	71.8	
2019-02-01 19:24:25.922	-29.79	25.20	54	336.1	227.1	13	15		75.9	67.8	
2019-02-01 19:12:42.451	-29.86	25.41	62	351.5	301.0	17	4	2050	78.6	62.3	
2019-02-01 19:26:48.376	-29.56	25.04	41	332.9	179.6	8	13	1930	86.2	65.1	
2019-02-01 20:09:16.344	-29.62	25.20	66	344.2	369.6	6	30	3045	78.4	61.2	
2019-02-01 20:38:25.718	-28.61	25.53	68	431.1	427.4	8	32	2200	79.3	53.1	
2019-01-29 19:33:50.302	-29.40	24.33	50	285.2	124.0	19	24	1360	83.7	66.0	
2019-01-29 20:25:41.984	-29.51	25.18	38	347.6	144.7	8	1	3060	85.0	62.0	
2019-01-29 20:38:40.528	-29.45	25.18	67	350.6	148.2	11	1	2160	87.0	62.0	
2019-01-29 19:17:59.218	-30.13	24.35	70	245.9	93.3	19	1	1680	83.3	68.5	
2019-02-01 19:55:34.857	-29.35	25.44	52	378.3	204.7	9	25		74.1	57.9	
2019-02-01 20:15:43.526	-29.02	25.32	92	387.6	425.3	7	25		70.7	50.0	
2019-02-01 19:24:26.151	-30.05	24.90	32	297.8	146.4	9	16		80.8	62.7	

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