PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 65 (2003) 499–508

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Current moment in sprite-producing lightning

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Abstract

Studies of sprite-producing lightning have revealed much of what we currently know about the mechanisms responsible for this phenomenon. With a combination of new and previous results, we summarize the currently known quantitative characteristics of this special class of lightning. This information has come primarily from the quantitative analysis of the electromagnetic fields produced by distant lightning. The long range of this technique has made it especially powerful, but there are important limitations on what can be measured that are related to the bandwidth of the measurement system. The lightning charge moment change required to initiate sprites varies across a relatively wide range, from approximately 100 –2000 C km. Note that this is not the total charge moment change in sprite producing lightning, which is by definition greater than the initiation threshold. This range is in very good agreement with the predictions of streamer-based sprite modeling. We also summarize the strong evidence, from a variety of sources, in favor of sprite currents as the origin of ELF pulses seen in a significant fraction of sprite events. The largest events show sprite current moment amplitudes of ∼1000 kA km and sprite charge moment changes of at least 1200 C km, and perhaps significantly more. Lastly, we show that delayed sprites are generated from very strong continuing currents (20–60 kA km) following a +CG return stroke. In the few cases analyzed, this current generates a charge moment change from 2000 to 6000 C km at the time of sprite initiation, which appears to be consistent with theoretical predictions of larger charge moment changes required for delayed sprite initiation. This current can be detected and analyzed with distant, sensitive ULF magnetic field measurements. Although much is known about sprite-producing lightning, there remain some fundamental yet unanswered questions about the lightning–sprite relationship. We expect that at least some of these will be answered in the relatively near future.

Keywords: Sprite; Lightning; Charge moment change; ELF propagation

1. Introduction

There have been two main thrusts in experimental sprite research since their discovery a little more than a decade ago, both with the goal of fundamentally understanding the phenomenon. One has been to document and interpret the morphological and spectral properties of their optical emissions. Optical measurements with ever-improving spatial and temporal resolution have clearly shown that sprites are composed almost solely of small-scale (∼100 m and less) streamers (Gerken et al., 2000) and develop on a variety of temporal scales, from submillisecond (Stanley et al., 1999) to hundreds of milliseconds (Stenbaek-Nielsen et al., 2000).

The other, which is the focus of this paper, has been to determine the characteristics of the lightning responsible for generating sprites. Studies of sprite-producing lightning have also made rapid progress. The earliest work (Baccippio et al., 1995) showed a clear temporal correlation between large positive cloud-to-ground (CG) lightning strokes and sprites. Since then, analyses of the electromagnetic radiation from lightning have quantified the charge transfer in sprite producing return strokes (Cummer and Inan, 1997; Bell et al., 1998; Huang et al., 1999) as well as discovered other processes in the mesosphere (Cummer et al., 1998) and in lightning (Cummer and Füllekrug, 2001) associated with the phenomenon.

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doi:10.1016/S1364-6826(02)00318-8

These studies have all been based on the quantitative analysis of the distant (more than several hundred km) electromagnetic fields produced by the lightning and sprite event. Although details have been given elsewhere, we summarize this general analysis technique, focusing specifically on the measurement limitations and how they affect the scientific interpretation of the data. We then present some new results on three issues directly related to the quantitative characteristics of sprite-producing lightning. The first is the lightning charge moment change at the time of sprite initiation. Measurements of this parameter provide a important and direct test for model predictions, but has not been well-measured previously due to limitations of imaging time resolution and limits on the duration or time resolution of extracted current moment waveforms. Some new measurements, designed to avoid these limitations, are presented that bound this charge moment change in a range that agree well with previous measurements and with current theories.

The second issue is the quantitative characteristics of lightning that produces sprites that are significantly delayed (more than 10 ms or so) from a cloud-to-ground (CG) return stroke. We verify and summarize the conclusions of Cummer and Füllekrug (2001) that unusually intense and long-lasting continuing currents are responsible for the small number delayed sprites examined so far. We also present a simple but accurate analytical calculation to convert quasi-steady magnetic field amplitude to quasi-steady current moment. The great advantage to detecting continuing currents through the quasi-steady magnetic field is that the slow r^{-1} amplitude decay of the field enables continuing current measurement from much longer distances than other methods, such as electrostatic field measurements.

The last issue is the existence and characteristics of sprite currents. It is now commonly (but not quite universally) believed that certain extremely low frequency (ELF) pulses during some sprite events originate in the sprite itself from mesospheric electrical currents. We summarize the evidence in favor of this interpretation, and we analyze some of the biggest events recorded during the summer of 2000 to determine the magnitude of the largest sprite currents.

Although much is known about sprite-producing lightning, there remain some fundamental yet unanswered questions about the lightning–sprite relationship. We discuss some of these that are related to the issues addressed in this work, and we expect that at least some of these will be answered in the relatively near future.

2. Analysis of distant electromagnetic fields

Current theories suggest that the most important factor in sprite generation is the vertical charge moment change in a lightning stroke. The relatively sustained ($\gtrsim 1$ ms) quasi-electrostatic field in the mesosphere after a lightning stroke are proportional to the lightning charge moment change, and it is this electric field that can drive electric breakdown and streamer development (Pasko et al., 1997b, 2000) and runaway relativistic electron breakdown (Yukhimuk et al., 1998; Lehtinen et al., 1999). Observations of sprite spatial structure agree very well with the predictions of conventional breakdown models (Pasko et al., 1998a), and recent calculations (Lehtinen et al., 1999) indicate that optical emissions from relativistic breakdown will be negligible relative to those from conventional breakdown, but the existence of terrestrial gamma ray bursts suggests that relativistic electron breakdown occurs at least occasionally (though perhaps not connected with an individual sprite). Other factors may contribute to sprite generation by lowering the electric field threshold required to initiate conventional breakdown. Gravity wave-induced neutral density depletions (Rowland et al., 1996; Pasko et al., 1997a) and meteoritic dust (Zabotin and Wright, 2001) have been proposed as such factors, and observations seem to indicate that charge moment is not the only factor leading to sprites (Hu et al., 2001). Nevertheless, substantial mesospheric electric fields are required in any case, and it is the lightning charge moment change that generates this field.

Unfortunately, commonly used techniques for measuring charge moment changes in lightning strokes, specifically direct measurement of the lightning current or analysis of electrostatic field changes during lightning, are inherently local measurements. Sprite-producing lightning, though not uncommon, is sufficiently widely distributed that even the two month STEPS campaign during the summer of 2000 captured relatively few sprites within the primary range of its ground instruments, despite detecting more than 1000 sprites overall (W. Lyons, personal communication).

The most successful sprite-related charge moment change measurements to date have been based on the quantitative interpretation of *distant* electromagnetic fields produced by the lightning discharge. Fundamentally, this technique is similar to the interpretation of local electrostatic field changes; one measures electromagnetic field component at a known distance from the source, and quantitatively analyzes the data in terms of charge motion or current in the lightning stroke. The main difference between the distant field technique and the local, electrostatic field technique is that the relationship between electrostatic fields and charges (Coulomb's Law) is a simple relation. The relationship between distant electromagnetic fields and currents involves wave propagation that is strongly influenced by the anisotropic, dispersive, and inhomogeneous ionosphere. Calculating the distant fields from a given discharge is usually not a straightforward problem, but it must be tackled to quantitatively interpret any measurements.

Although lightning is a very broadband electromagnetic radiator, the only frequencies that can propagate much beyond a few hundred kilometers from the stroke are very low frequency (VLF, 3–30 kHz) and lower. Because the wavelength at these frequencies is generally longer than the lightning channel, and the wave period is slower than the internal return stroke dynamics, the effective source of VLF and lower frequency radiation from lightning is the only the length-integrated current or current moment, $M_i(t)=\int i(t)\,dl$. This limits the information about the source lightning in VLF and lower frequencies to only the current moment waveform. Fortunately, this is the quantity of most interest in the sprite problem.

2.1. Formulation and example

The problem can be generalized in the following way: given a measured electromagnetic signal $F(t)$ from distant lightning in a known frequency range, what quantitative information can be extracted about $M_i(t)$? The relationship between these quantities is in general complicated but linear, implying that the convolution relationship $F(t) = \int_{-\infty}^{\infty} M_i(\tau)h(t-\tau)\,d\tau$ holds, where $h(t)$ is the field waveform produced by an impulsive current moment source. The quantity $h(t)$ necessarily includes effects from the propagation and the system frequency response. Assuming $h(t)$ can be realistically computed from analytical (Greifinger and Greifinger, 1979) or numerical (Cummer, 2000) propagation models, the problem becomes the following: given a modeled and (hopefully) realistic $h(t)$, what is the source waveform $M_i(t)$ that, when convolved with $h(t)$, agrees most closely with the measured fields $F(t)$? There are a number of standard techniques for solving this ill-posed deconvolution problem, and Cummer and Inan (2000) describe one that has been successfully applied to this problem.

Fig. 1 shows an example of this analysis. The top panel shows a filtered ELF (∼100–1500 Hz) magnetic field waveform received during a sprite at 061224.008 UT on July 4, 2000, and also a model-calculated ELF impulse response for the same propagation distance radiated by a 500 C km impulsive source. Although the peak amplitudes are the same, the measured field waveform has a broader main pulse and, importantly, does not drop below zero as quickly as the impulse response. This implies that the actual source current was not impulsive but remained on for a longer period, and therefore contained a greater charge moment change than just 500 C km. The middle plot shows the current and charge moment waveforms extracted from the data using the method described by Cummer and Inan (2000). It is clear that the actual source current was not impulsive and contained a total charge moment change of nearly 4000 C km. The bottom plot demonstrates that the extracted current moment waveform is reasonable, assuming $h(t)$ is accurate, by comparing the observed waveform with the modeled waveform computed by convolving the modeled impulse response with the extracted current moment. These waveforms are nearly identical, which implies that extracted current moment is consistent with the data.

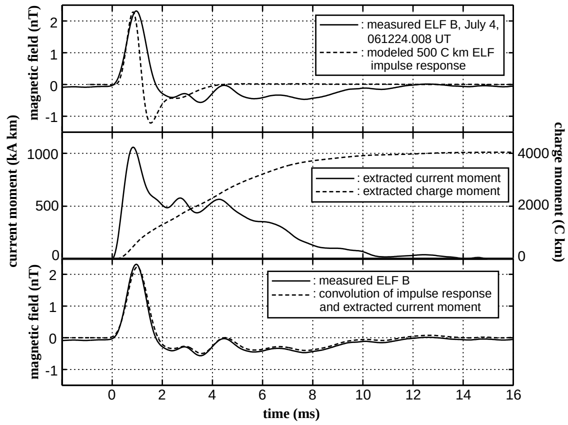

Fig. 1. Demonstration of a current moment measurement from a distant ELF magnetic field waveform. The top panel shows the measured magnetic field waveform and the modeled waveform radiated by a 500 C km impulsive source. The middle panel shows the current moment and charge moment change waveforms extracted from the data using the modeled impulse response. The bottom panel compares the measured waveform with that produced by the convolution of the modeled impulse response and the extracted current moment waveform. The good agreement ensures that the extracted current moment waveform is consistent with the data.

2.2. Limitations

At first glance, the simple relationship between the measured fields and the source current moment suggests that $M_i(t)$ can be measured without limitation. Unfortunately, the combination of noise and limited system bandwidth do constrain the measurable $M_i(t)$. Exactly how $M_i(t)$ is limited is a complicated issue. Qualitatively, the upper limit to the system frequency response imposes an upper limit to the spectrum of the recoverable current moment waveform $M_i^r(t)$. Thus $M_i^r(t)$ is a low pass filtered version of the actual current moment $M_i(t)$. Note that this limitation does not limit the measurability of the *total* charge moment change $M_q(t=\infty) = \int_0^{\infty} M_i(\tau)\,d\tau$; the integral over all time of a function $f(t)$ and a low pass filtered version $f_{\text{filt}}(t)$ are always the same (Bracewell, 1986). The upper frequency limit merely limits the resolvable speed of charge removal.

Because the VLF spectrum from lightning is difficult to interpret in this way due to complicated waveguide propagation effects, most studies have limited the analyzed data to the ELF band below ∼1.5 kHz. Numerical experiments with a propagation impulse response bandlimited in this way show that current pulses narrower than ∼0.8 ms cannot be resolved and are spread over the full 0.8 ms. The information discarded through this filtering is only the sharpness of the current moment on time scales faster than this. For the sprite problem, the quasi-static nature of the important mesospheric electric field implies that submillisecond variations are not very important (although this fast time scale information is relevant for elves and perhaps for sprite halos (Barrington-Leigh et al., 2001). Because the resolvable pulse width scales inversely with system bandwidth, a Schumann resonance (SR) band system with an upper frequency limit of 120 Hz, such as that used by Huang et al. (1999), will have a minimum resolvable pulse width of ∼10 ms.

The effect of the low frequency signal limit is harder to quantify and, for the sprite problem, more significant. Although most systems have a lower cutoff frequency below which the signal response falls with decreasing frequency, they still admit usable signal below this frequency. And because this frequency response is compensated for in the modeled system response, the lower cutoff frequency by itself does not limit the extractable current moment waveform. Instead, the signal to noise ratio (SNR) frequency dependence is of primary importance. In general, background and system noise increases as frequency decreases, and there will be a frequency below which the noise dominates the signal. Using frequencies below this frequency in the data inversion will lead to fitting the noise instead of fitting the signal, giving incorrect results.

The practical effect of excluding the lowest frequencies from the reconstruction is to limit the duration of the current moment waveform that can be reliably extracted. As a rough estimate of this effect, if we take the unity SNR frequency f_{SNR} as the minimum usable frequency in the data, then a step current will be measured as an exponentially decaying current with a time constant of $(2\pi f_{SNR})^{-1}$. For example, the ELF magnetic field recorded at Duke University during the summer of 2000 has a unity SNR frequency of approximately 20 Hz, suggesting a reliable current moment duration of approximately 1 time constant or 8 ms. In reality, this estimate is somewhat pessimistic, and numerical experimentation with simulated data and real noise indicates that current moment waveforms from our ELF data can be reliably extracted to between 10 and 20 ms after the return stroke. The specific duration depends on the SNR and thus the signal amplitude. Lower frequency data, such as SR-band measurements, are better able to measure long duration currents, but usually at the expense of time resolution due to the reduced high-frequency limit. Obviously, the best choice is very broadband data of the type analyzed by Cummer and Füllekrug (2001) and below in Section 5.

Provided these limitations are carefully considered in any analysis method, reliable and accurate current moment waveforms can be extracted from very distant electromagnetic field measurements. This general technique is thus a very powerful tool for analyzing lightning, particularly the strong lightning so relevant to sprite generation.

3. Charge moments

The first reported work relating sprites and lightning found, from SR-band lightning emissions, that CG strokes that move a lot of charge to ground are usually associated with sprites (Boccippio et al., 1995). This work did not quantify the charge transfer, however, and since then a number of papers have reported measured charge moment changes in sprite-producing lightning measured from distant ELF and SR-band electromagnetic field observations. All of this work used analysis methods related to that described above. Analysis of ELF measurements (Cummer and Inan, 1997) showed charge moment changes of several hundred to several thousand C km in the first 7 ms of sprite-producing +CG strokes, which demonstrated the extreme magnitude of some sprite-producing discharges and, importantly, showed that the charge moment changes were consistent with existing theories. SR-band measurements (Huang et al., 1999) showed similar charge moment changes of several hundred to several thousand C km for the entire duration of sprite-producing discharges. However, neither of these studies addressed the important issue of charge moment change at the time of sprite initiation. Sprites initiate from ∼1 ms to hundreds of milliseconds after a return stroke, thus the total charge moment change in a lightning discharge can substantially exceed that which initiated the sprite, and the charge moment change after 7 ms may either overestimate or underestimate that which initiated the sprite.

A combined analysis of ELF emissions and video timing of sprites during a single 15 min period (Bell et al., 1998) found that sprites initiated after 200–1100 C km of charge moment change, but this analysis suffered some ambiguity from the 16.7 ms uncertainty in the sprite initiation time and only measured sprites in a very limited time period. A combination of high-speed video images and ELF magnetic fields on a single day (Cummer and Stanley, 1999) found that most sprites initiated after charge moment changes of 300–1100 C km, spanning lightning-sprite delays of 2–11 ms. Substantially larger charge moment changes (up to 6000 C km) have been observed to initiate daytime sprites) (Stanley et al., 2000), which is expected because the higher daytime mesospheric conductivity inhibits the penetration of quasi-electrostatic fields to higher altitudes.

Although these numbers are in agreement, they are based on limited data and do not give much of a sense of the extreme values or of the overall distribution of charge moments. During the STEPS (Severe Thunderstorm Electrification and Precipitation Study) campaign of the summer of 2000 the ELF–VLF magnetic field was recorded continuously at Duke University, one goal being to record and analyze the signals from a large number of sprite-producing discharges. In all, ELF waveforms were recorded during almost 900 sprites on 17 different days. We have thus far focused on a subset of around 80 sprites for which, due to a combination of timing and SNR, the lightning charge moment change at sprite initiation could be accurately measured. Details and analysis of this charge moment distribution are given by Hu et al. (2001). In Figs. 2 and 3, we show three of the largest and two of the smallest sprite-producing discharges of the campaign. The top panel of each contains

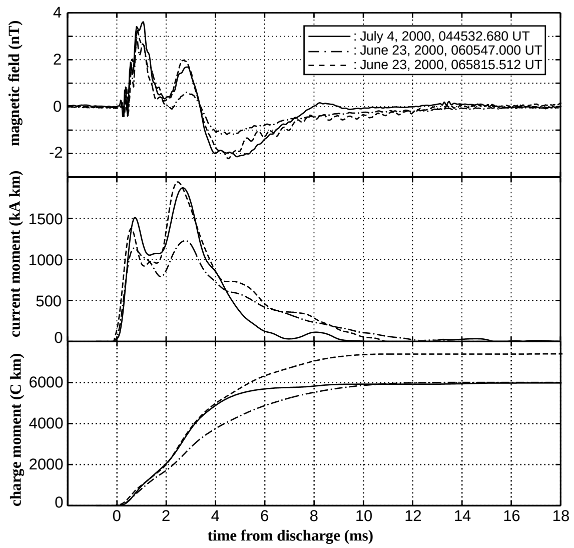

Fig. 2. ELF total horizontal magnetic field waveforms, extracted current moment waveforms, and cumulative charge moment waveforms for three of the biggest sprite-related lightning discharges during the summer of 2000. The total charge moment change in each of these is greater than 6000 C km in 10 ms or less. We emphasize that this includes fast charge moment change in the sprite itself.

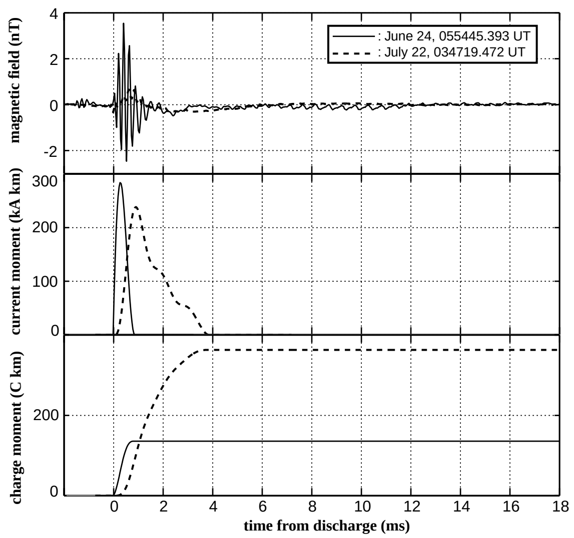

Fig. 3. ELF magnetic field waveforms, extracted current moment waveforms, and cumulative charge moment waveforms for two of the smallest sprite-related lightning discharges during the summer of 2000. The total charge moment change in each of these is only a few hundred C km, but was still sufficient to generate a sprite within less than 6 ms of the return stroke.

the raw ELF–VLF total horizontal magnetic field waveform from the event, and the middle and lower panels show the extracted current moment and charge moment variations for each of these events. The total charge moment changes in the three largest events are huge: from 6000 C km to more than 7000 C km in approximately 10 ms. We emphasize, however, that this total charge moment change is greater than the charge moment change that initiated the sprite. In fact, the sprite current pulses (see Section 4 below) at $t = 2$ ms in these events enables us to accurately calculate the lightning charge moment change up to the time of sprite current initiation. This value is between 1800 and 2000 C km in all three cases. Because charge continues to move after this time, we suggest that this is an upper limit to the charge moment change required to initiate a sprite relatively quickly ($\lesssim$ 5–10 ms) after the lightning. More charge may be required to initiate a sprite that is substantially delayed from a return stroke (Pasko et al., 1997b).

We also emphasize that this total charge moment includes sprite current and is thus not all in the lightning channel. It is difficult to separate and thus independently quantify the lightning and sprite charge moment change components. These were highly energetic sprites that may have generated ionization and enhanced conductivity over a substantial altitude range. The non-lightning charge moment change in this case may thus have been a substantial fraction of the total charge moment change that occurred after $t = 2$ ms when the sprite currents turned on. Nevertheless, the lightning charge moment change at sprite initiation is measured accurately.

In contrast, Fig. 3 shows that sprites were also generated by charge moment changes of only a few hundred C km. Video timing in each of these cases constrained the sprite initiation time to be less than 6 ms after the return stroke. We can thus place upper limits on the initiation charge moment change of 370 and 120 C km. The sprite produced by only 120 C km was extremely small (W. Lyons, personal communication) and is probably close to the lower limit of the charge moment change that can produce a sprite. Note that the raw magnetic field waveform for this event contains more VLF energy than the other four signals shown. This indicates that the charge transfer, although smaller, was faster in this case, which may have contributed in some way to the generation of a sprite after such a small discharge. But there were a significant number of sprites produced by charge moments in the 300–400 C km (Hu et al., 2001) like the other shown here. This lower observational limit of a few hundred C km for sprite-producing discharges does not imply that every discharge of this strength produces a sprite. To the contrary, a statistical analysis of the charge moment changes shows that discharges of a few hundred C km rarely ($< 10\%$ of the time) produce sprites.

These new measurements and previously reported measurements are all roughly self-consistent and suggest that sprites that initiate relatively quickly after a return stroke initiate after lightning charge moment changes varying from a few hundred to a few thousand C km. These numbers are very consistent with recent streamer-based modeling of sprite development (Pasko et al., 2000), which shows that large sprites are generated by 1000 C km discharges and very small sprites are generated by 100 C km discharges. Whether the predicted relationship between sprite size and lightning strength is correct has not yet been investigated, but would be an important test of existing theory.

4. Sprite currents

Thorough study of ELF magnetic and electric field signals has shown that unusual pulses are sometimes observed during sprite events. These pulses are distinct from those generated by a lightning return stroke because they do not contain any energy at frequencies above approximately 1 kHz. This implies that the source current that radiated the pulse does not contain any energy above ~1 kHz, and therefore has a risetime and falltime much slower than the current in an ordinary return stroke. Fig. 4 shows an example of this phenomenon recorded with a 100 Hz–5 kHz bandwidth sensor (these frequencies are the half-power points and thus the signal contains energy outside this range). The field pulse from the return stroke clearly contains substantial energy above 1 kHz, as indicated by the fast time oscillations at the start of the pulse; the second pulse 5 ms after the lightning does not.

In 1996, P. Krehbiel and colleagues at New Mexico Tech suggested that these pulses were radiated by high altitude electric current in the sprite itself and not by a lightning process. Evidence strongly in favor of this interpretation came from a combined analysis of the electromagnetic fields and high time resolution optical emissions. The rise and fall of the source current of this second pulse, measured using the technique described in Section 2, were found to be temporally coincident with the rise and fall of the large-scale sprite brightness (Cummer et al., 1998). This relationship has been verified in additional studies (Cummer and Stanley, 1999; Reising et al., 1999). The implication is that the source current turns on when the sprite initiates, and decays as the sprite decays, strongly suggesting that the current source is in the sprite itself and not the lightning.

Unfortunately, a vertically flowing current that radiates only at ELF and lower generates distant electromagnetic fields that are essentially independent of source altitude. The distant fields alone thus contain no information about the source altitude. However, the indirect evidence is *strongly* in favor of the sprite current hypothesis. Pulses of exactly this type have not been observed in lightning without a sprite, but are fairly common in sprite-producing lightning. These pulses have always been observed precisely time-correlated (within a few hundred microseconds) with the sprite brightness; they have not been observed to come even slightly before or after the sprite. The source location of the pulses can be laterally displaced from the position of the lightning return stroke by as much as 60 km (Füllekrug et al., 2001), implying that these pulses cannot be traditional M-components (Rakov et al., 2001) that flow in an existing return stroke channel. And, electromagnetic modeling has shown that

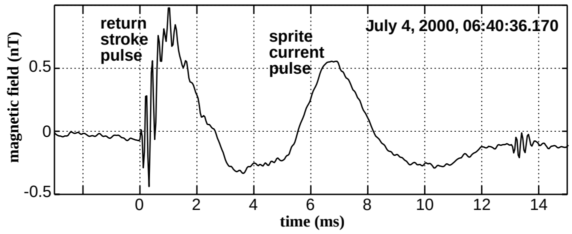

Fig. 4. Example of an ELF waveform with a sprite current pulse. The return stroke pulse starting at $t = 0$ contains significant VLF energy, while the second pulse at $t = 5$ ms does not. This indicates a non-return stroke origin for this pulse, and evidence is strongly in favor of this pulse being generated in the sprite itself.

these pulses are of the magnitude and duration expected when significant electrical conductivity is present in the sprite (Pasko et al., 1998b). Direct evidence would be satisfyingly conclusive, but in light of the existing data, rather bizarre and unlikely circumstances are required in order for them *not* to be sprite currents.

Sprite currents can be substantial in magnitude. The ELF signals in Fig. 2 all contain clear sprite current pulses that initiate ~2 ms after the start of the lightning return stroke. These sprite current pulses are among the largest observed during the entire STEPS campaign, which is not surprising since these are also among the most energetic overall discharges observed. Again, there is no clear way to separate the sprite and lightning current moments in these waveforms, but at a minimum the discrete second pulse is almost certainly sprite current only (note that this pulse is superposed on a slowly varying current moment component that could be lightning current, sprite current, or both). These events thus contain a peak sprite current of at least 1000 kA km and a total sprite charge moment change of at least 1200 C km. Assuming a conducting channel length of 40 km in the sprite (this is probably within a factor of two of the true length), this implies 25 kA flowing throughout the length of the sprite and a total of 30 C moved from the ionosphere to the base of the sprite.

In light of the quasi-static 1D analytical solution of this problem (Pasko et al., 1998b), it is not surprising that sprite currents and charge moment changes are so substantial. We note that even without a sprite, positive (negative) charge moves down from high altitudes after a positive (negative) CG stroke to cancel the unshielded charge left after the lightning (Greifinger and Greifinger, 1976). This charge motion is sufficiently slow, however, that its signature in distant electromagnetic fields is not very distinct. The sprite serves as a conducting channel to accelerate this charge motion, increasing the instantaneous currents and making its signature more distinct in the distant fields. In the limit of a conducting channel (i.e., sprite) extending from the bottom of the ionosphere to the cloud-top altitudes, a charge equal to the charge removed in the lightning q is moved from the ionosphere to the bottom of the sprite. This gives a maximum possible sprite charge moment change of $q(h_i - h_q)$. This is the case where a total charge q moves through the conducting channel from the ionosphere at altitude h_i down to the charge removal altitude h_q. Note that this can be many times larger than the charge moment change qh_q in the lightning discharge alone if the conductivity in the sprite extends to sufficiently low altitudes. This total mesospheric charge moment change is independent of the width of the conducting channel; current will flow in any channel a long as the total charge moved downward is not sufficient to cancel the charge imbalance left after the CG stroke.

The fundamental discovery of strong high altitude electric current is exciting in its own right, but sprite currents also tell us something about the sprite itself and the lightning that created it. They provide a mechanism to constrain the overall conductivity and thus ionization in the sprite, and they can also constrain the electric field strength at sprite altitudes (Pasko et al., 1998b). Interestingly, analysis of the Duke University ELF data from the summer of 2000 indicates that sprite currents appear in only approximately 10% of sprite events. The difference between sprites that do and do not contain sprite currents is not understood, although limited observations suggest that subsequent upward streamers may be present only in sprites that do contain a sprite current (Cummer and Stanley, 1999).

5. Delayed sprites

Sprites frequently initiate tens of milliseconds or longer after any CG return stroke. Studies of this lightning-sprite delay for many events show that a substantial fraction of sprites (∼33%) are delayed more than 30 ms (Hu et al., 2001). It is difficult to calculate the lightning charge moment change responsible for initiating these sprites; in fact, only recently has it been determined what process connects the temporally separated return stroke and sprite. Continuing currents were an obvious candidate for this process, but they would have to be very high amplitude to move the quantity of charge required to initiate a sprite long after a return stroke. Because dielectric relaxation reduces the electric field at higher mesospheric altitudes, delayed sprites would have to initiate at lower altitudes, where the breakdown electric field (and thus the required charge moment change) is higher (Pasko et al., 1997b).

As discussed above in Section 2.2, many ELF sensors are not sensitive enough at the lowest frequencies to detect the fields from any long-lasting, quasi-static continuing current. Lower frequency SR-band sensors are sensitive to long duration continuing currents, but their ordinarily limited time resolution makes it difficult to parameterize the current beyond a single exponential time constant in the discharge. This does not accurately describe a short return stroke pulse followed by a nearly constant continuing current, which makes it difficult to accurately determine the

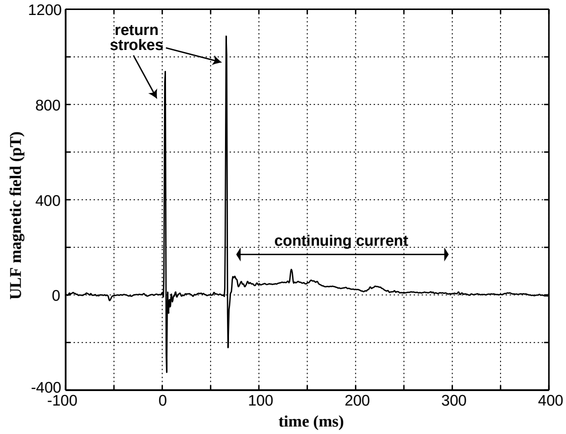

Fig. 5. Example of continuing current signature in broadband ULF magnetic field data. The two short pulses are radiated by return strokes. Following the second return stroke (but not the first), the field remains elevated for approximately 200 ms. This the quasi-static magnetic signature of continuing current.

charge moment change at the time of sprite initiation. These limitations have made it difficult to quantify charge moment changes that initiate delayed sprites and to positively detect a continuing current between the return stroke and sprite.

Unambiguously measuring the characteristics of the lightning responsible for delayed sprites requires a sensor that is very sensitive at low (∼10 Hz and below) frequencies, but has enough bandwidth and time resolution to resolve current variations on the order of 1 millisecond (i.e., an upper frequency limit of at least a few hundred Hz). Three such sensors, composed of magnetic coils and amplifiers with a flat frequency response from 0.1 to 500 Hz and data sampled at 2048 Hz, were operated by M. Füllekrug during the summer of 1998. The electromagnetic signals recorded by this system unambiguously showed the signature of long duration (hundreds of milliseconds), intense (as big as 60 kA km) continuing currents following big +CG strokes that produced sprites (Cummer and Füllekrug, 2001). The data recorded in Saskatoon, Canada following a 1885 km distant +CG on July 29, 1998 at 04:25:50.102 UT, shown in Fig. 5, demonstrate this especially clearly. The first pulse in this ULF–ELF magnetic field data corresponds to an NLDN-recorded return stroke. The magnetic field quickly returns to nearly zero after the stroke, as expected for a lightning current that does not persist longer than a few milliseconds. A second return stroke occurred 60 ms later, after which the magnetic field does *not* return to zero but remains elevated for approximately 200 ms. This quasi-static field signature is only detectable at this distance in magnetically quiet locations where the system noise level is around 10 pT or less.

The lightning current moment waveform from these fields can be measured from these fields by the same general procedure described in Section 2: quantitatively model the

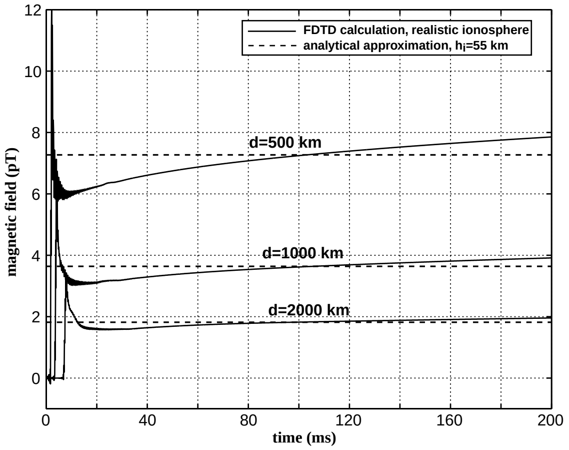

Fig. 6. Transverse horizontal magnetic field waveforms produced by 1 kA km step currents at a variety of distances from the source. The solid lines are those calculated using a numerical full-wave finite difference model, and the dashed lines are from the simple quasi-static approximation. These curves can be used to measure continuing current amplitude from distant ULF magnetic field recordings.

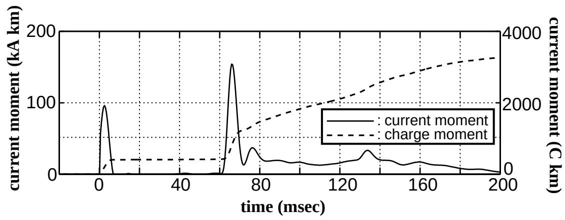

Fig. 7. The current moment and charge moment change waveforms extracted from the ULF data in Fig. 1. The data indicate a large continuing current of 20 kA km that lasts for longer than 200 ms.

distant fields from an impulsive or other known source (such as a step function), and find the appropriate sum of sources that gives model fields very close to those observed. To analyze these fields, Cummer and Füllekrug (2001) used a finite difference electromagnetic model of the Earth-ionosphere waveguide (Cummer, 2000) to make the simulations as realistic and accurate as possible. But a relatively simple magnetostatic calculation shows that a quasi-static horizontal magnetic field as observed is produced by a steady vertical electric current (i.e., continuing lightning current). Assuming a steady current I flowing between an altitude h_s and the ground, the horizontal magnetostatic field produced by this current and its ground and ionospheric images (assuming a sharp ionosphere at altitude h_i) is $B_\phi = (\mu_0/2\pi r)(h_s/h_i)I$. This equation assumes that the discrete physical and image current segments can be approximated by an equivalent infinite line current, which is valid if $r \gtrapprox h_i$.

Fig. 6 shows the full-wave FDTD-calculated horizontal magnetic field at ground level produced by a 1 kA km step discharge at a variety of distances from the source. After the initial transient, the field increases slightly in time because the effective height of the ionosphere decreases with time (Greifinger and Greifinger, 1976), but for the most part a constant current produced a constant magnetic field. Also shown is the static magnetic field produced by a constant 1 kA km current and its image currents assuming an ionospheric height of 55 km. This very simple model is a good approximation to the full wave calculations. This quasi-static magnetic field decays with distance only as r^{-1}, far slower than the r^{-3} electrostatic field signature of a continuing current. Continuing currents can thus be detected from this magnetic field signature very far from the source.

Fig. 7 shows the current moment waveform extracted from the observed fields shown in Fig. 5. The continuing current amplitude is approximately 20 kA km, which can also be estimated directly from Figs 5 and 6 by the following. At $r = 1885$ km, the quasi-static magnetic field is $\sim$2.5 pT/(kAkm); therefore the observed field strength of 50 pT corresponds to approximately 20 kA km of continuing current.

Cummer and Füllekrug (2001) only analyzed three delayed sprites, but found that long continuing currents of 20 –60 kA km followed the return stroke in all cases. This continuing current forms the important causal connection between the return stroke and the delayed sprite initiation. Importantly, the charge moment change in the continuing current exceeded that in the return stroke, in some cases substantially. When the continuing current is included (which we suggest it may not be when the current is measured from higher frequency ELF data), the total charge moment change in these three cases (varying from $\sim$2000 to 6000 C km) agreed reasonably well with the theoretically expected charge moment change required to initiate a delayed sprite. These measurements also have implications for lightning itself, as these continuing currents are extremely large and persist at least as long as ordinary, much lower amplitude continuing currents. How common these extreme continuing currents are an whether they are involved in every delayed sprite has not yet been addressed. It seems very likely that they are involved in all delayed sprites, and are therefore not especially rare.

6. Some unanswered questions

From optical and radio studies, the amount now known about sprites is substantial, especially considering they were first discovered little more than a decade ago. These studies have had an impact in other scientific areas as well, particular lightning, where they have demonstrated that strong +CG lightning is more common than previously thought. But some important questions regarding sprite generation remain unanswered (perhaps more accurately, unaddressed) that ULF–VLF radio studies could lay an important role in answering. Some of these have been suggested in the previous section but are now summarized here. This is not meant to be an exhaustive list, but these issues are some that appear both compelling and accessible.

- What, if any, factors other than vertical lightning charge moment change influence sprite generation?
  Conventional breakdown and streamer theory has very successfully explained many features of sprites. However, observations do show that a wide range of vertical charge moment changes can initiate sprites. It is possible that the morphological differences between low and high charge moment sprites can be completely explained by electric field differences in the context of conventional breakdown theory. But the fact that sprites appear to initiate only sometimes after similar small lightning suggests that other factors are involved. It has been suggested that horizontal charge motion may increase the high altitude electric field without being detectable in distant electromagnetic fields (Bell et al., 1998), although this requires a horizontal current direction opposite to those usually associated with horizontally extensive lightning. External mesospheric factors that can enhance the probability of dielectric breakdown may play a role.
- Why are there so few sprites produced by negative discharges?
  Although asymmetry in the electrical breakdown process does suggest that it takes larger electric fields to generate sprites after negative discharges than positive ones (Pasko et al., 2000), it is still surprising that sprites are almost never produced by negative lightning (except very rarely (Barrington-Leigh et al., 1999)). Lightning studies have shown that big charge moment change negative discharges are not significantly less frequent than positives (Huang et al., 1999), and modeling shows that comparably sized sprites should be generated by 1000 C km positive and negative discharges (Pasko et al., 2000). Are there big negative discharges that, according to theory, should have produced sprites but did not?
- Why are there only sometimes sprite currents?
  A significant fraction of sprites (approximately 10%) contain a clear sprite current ELF signature. This seems to be distributed evenly across lightning-sprite delays. There is clearly some fundamental difference between those sprites that have a sprite current and those that do not. Physically, what is that difference? It seems that there is some process, not present in all sprites, that creates substantial mesospheric ionization. Brief analyses of optical data have not suggest an immediately obvious answer (although sprite currents were found to be temporally aligned with late-initiating upward streamers (Cummer and Stanley, 1999) that may not be present in all sprites).

7. Conclusions

The quantitative analysis of distant electromagnetic fields radiated by lightning has generated much of what we currently know about sprite-producing lightning. This analysis, while relatively straightforward, is complicated by the need for an accurate propagation model, and there are a number of limitations of the technique that must be carefully considered when analyzing this kind of data. With a combination of new and previous analysis, three specific issues related to sprite producing lightning were discussed. The lightning charge moment change required to initiate sprites varies across a relatively wide range, from 100 to 2000 C km. Note that this is not the total charge moment change in sprite producing lightning, which is by definition greater than the initiation threshold. This range is in very good agreement with the predictions of streamer-based sprite modeling. A key unanswered question is whether sprite size is connected with charge moment change as predicted by the model. We also summarized the strong evidence in favor of sprite currents as the origin of ELF pulses seen in a significant fraction of sprite events. The largest events show sprite current moment amplitudes of $\sim$1000 kA km and sprite charge moment changes of at least 1200 C km, and perhaps significantly more. Lastly, we showed that delayed sprites appear to be generated from very strong continuing currents (20–60 kA km) following a +CG return stroke. In the few cases analyzed, this current generates a charge moment change from 2000 to 6000 C km at the time of sprite initiation, which appears to be consistent with theoretical predictions of larger charge moment changes required for delayed sprite initiation. This current can be detected and analyzed with distant, sensitive ULF magnetic field measurements. Future work is required to show whether these continuing currents are present for all delayed sprites.

Acknowledgements

The author would like to acknowledge discussions and ongoing collaborations related to this work with M. Füllekrug, W. Lyons, M. Stanley, and V. Pasko. Thanks also to J. Edeburn and the Duke Forest management for their exceptional help in setting up the experimental facility used in this work. This work was partially supported by NASA grant NAG5-10270.

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