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Video and photometric observations of a sprite in coincidence with a meteor-triggered jet event

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Abstract. Video and photometric observations of a meteor-triggered "jet" event in association with the occurrence of a sprite were collected during the SPRITES '98 campaign. The event raises interest in the question of possible meteoric triggering of upper atmospheric transients as originally suggested by *Muller* [1995]. The event consisted of three stages: (1) the observation of a moderately bright meteor, (2) the development of a sprite in the immediate vicinity of the meteor as the meteor reached no lower than ~70 km altitude, and (3) a slower-forming jet of luminosity that appeared during the late stages of the sprite and propagated back up the ionization trail of the meteor. The event is analyzed in terms of its geometry, its relevance to the meteor, and the implications to existing theories for sprite formation.

1. Introduction

The phenomenology of sprites and blue jets has been well documented in the 10 years since the first photographic evidence of upper atmospheric transients was reported [e.g., *Franz et al.*, 1990; *Lyons*, 1994; *Sentman et al.*, 1995; *Wescott et al.*, 1995; *Winckler et al.*, 1996]. However, the generation mechanisms for these processes have yet to be conclusively identified. In recent years, time-resolved filtered photometry and broadband spectroscopy measurements have begun to quantify the energetics of sprites and blue jets [*Mende et al.*, 1995; *Hampton et al.*, 1996; *Armstrong et al.*, 1998; *Suszcynsky et al.*, 1998], and high-resolution, high-speed imagery [e.g., *Nelson et al.*, 1998; *Stanley et al.*, 1999; *Inan et al.*, 1998] has produced unprecedented views of the temporal and spatial structure associated with these events. Such measurements provide valuable data against which to compare existing and new sprite and blue jet generation theories. For example, recent measurements [*Armstrong et al.*, 1998; *Suszcynsky et al.*, 1998; *Wescott et al.*, 1998] strongly suggest that significant amounts of N_2 ionization are produced in association with both sprite and blue jet occurrences. The energetic (>18.7 eV) electrons that are required to produce this ionization are, in fact, predicted by the quasi-electrostatic theories that invoke the runaway breakdown mechanism [e.g., *Roussel-Dupre et al.*, 1997; *Lehtinen*, 1997] and/or conventional breakdown [*Pasko et al.*, 1995, 1996a, b] and by the electromagnetic pulse theory [*Inan et al.*, 1991; *Taranenko et al.*, 1993a, b] for sprite, blue jet, and elve generation.

This paper presents ground-based video and photometric observations of a sprite and a related upward propagating "jet" of luminosity associated with the entry of a fairly bright meteor into the mesosphere. The event was captured during the SPRITES '98 campaign at the Yucca Ridge Field Station (operated by FMA Research) in Fort Collins, Colorado. The fortuitous injection of a trail of intense ionization into the mesospheric region above a sprite-producing thunderstorm may represent a unique opportunity to gain further insight into the initiating mechanism(s) for sprite and jet formation.

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2. Observations

The instrumentation consisted of two intensified Xybion video cameras (Model ISS-255) with 12° fields of view (FOV), a VLF receiver, and an array of co-aligned photometers covering (1) 580 to 900 nm with a 4° FOV, (2) 430 ± 5 nm with both a 4° and 6° FOV, and (3) 399 ± 5 nm with a 6° FOV. One of the cameras was operated in the "white light" mode with a spectral response in the 400 to 900 nm range, and the second camera was operated in the "blue light" mode with an effective passband of 350 to 475 nm [*Suszcynsky et al.*, 1998]. Each frame of video represents ~34 ms of integration time and consists of two sequential and nonoverlapping video fields (17 ms of integration/field). The video was Global Positioning System (GPS) time stamped to a precision of 1 ms. The VLF receiver operated over the 1 to 10 kHz range and was sampled both as an audio signal (on the sprite videotape) and by the data acquisition system. The photometers were manually triggered whenever a sprite was observed by using a 1 s record length with a 50% pretrigger setting. Data were sampled at 20 kHz and GPS time stamped to within a 1 μs precision by the data acquisition system. More detailed descriptions of the photometers are given by *Armstrong et al.* [1998] (6° FOV photometers) and *Suszcynsky et al.* [1998] (4° FOV photometers).

Figure 1 presents eight frames of white light video that summarize the event. The altitude scales in Figures 1f and 1g are based on an event range of 380 km. This range corresponds to a positive cloud-to-ground (CG) discharge that occurred during the video sequence (as detailed later in this section). The event occurred on August 2, 1998, UT over a 1.5 s time period beginning at 0444:54.811 UT with the initial appearance of a moderately bright meteor at ~106° azimuth and 14° elevation. Figures 1a–1d show the trajectory of the meteor in the

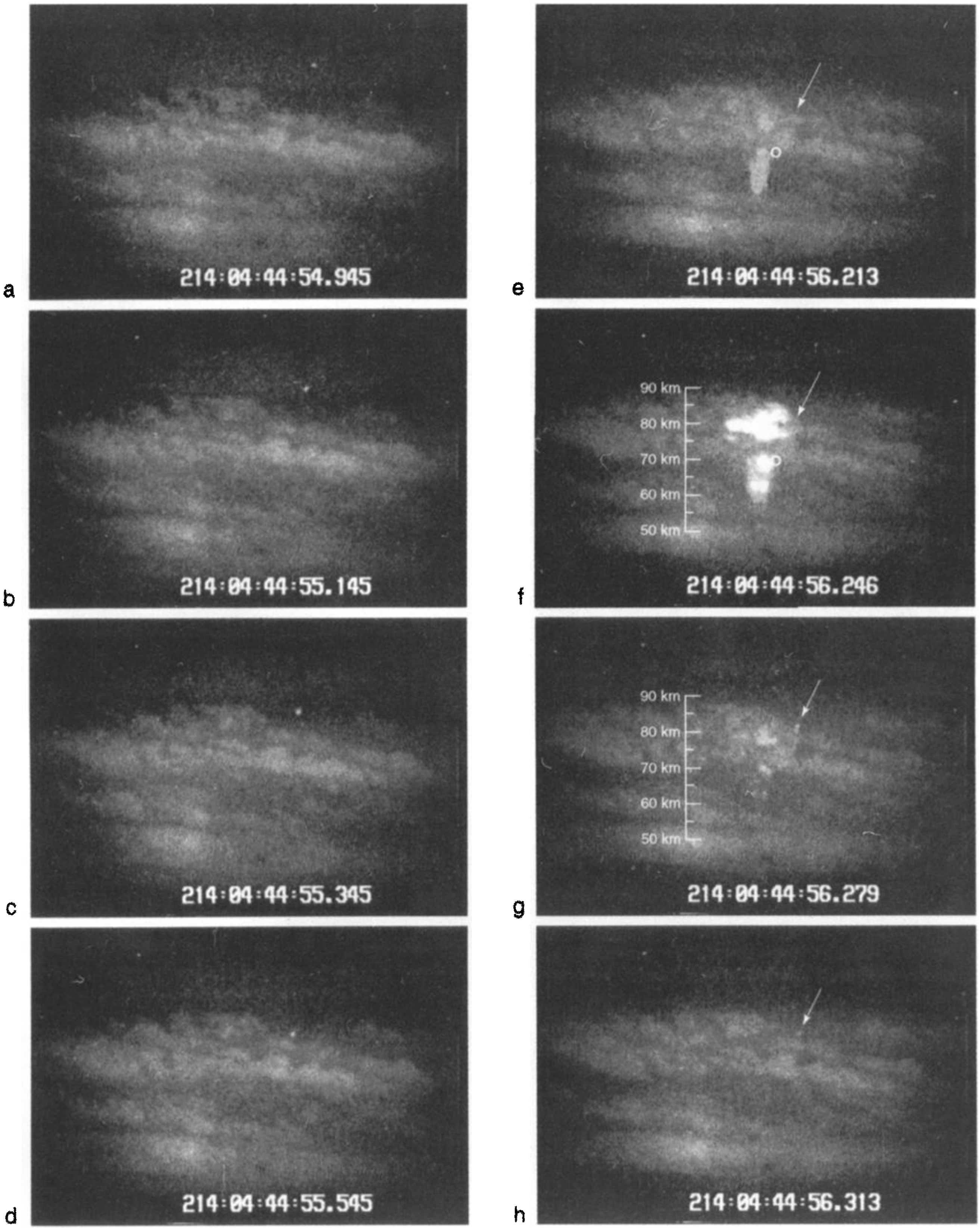

Figure 1. Video frames (33 ms/frame) of the event showing (a–c) the meteor during its trajectory, (d) the meteor just before initial obscuration by foreground clouds, (e) the first frame of the sprite with an arrow indicating the observed trajectory of the meteor and a circle indicating the position of the meteor at the time of the sprite, assuming that it continued to travel behind the foreground clouds at a constant velocity, (f) the second frame of the sprite showing an altitude scale and the same arrow and circle as in Figure 1e, (g) the third frame of the sprite and first frame of the jet with altitude scale and an arrow indicating the general path direction of the meteor, and (h) the second frame of the jet showing the same arrow as in Figure 1g.

upper right quadrant of each frame from a few frames after its initial appearance to just before it was obscured by foreground clouds. The apparent velocity of the meteor was ~27 km/s downward at an angle of ~30° from vertical. The velocity component along the line of sight is not known because of the single-station observation, so the 27 km/s value represents a lower bound to the actual meteor speed. Meteor velocities typically range from ~10 to 75 km/s [e.g., *McKinley*, 1961]. The apparent brightness of the meteor was conservatively estimated at third magnitude on the basis of magnitude comparisons with nearby stars. Although not shown, the meteor briefly reappeared through the clouds at 0444:55.779 UT for ~100 ms over the altitude span from 78 to 75 km.

Approximately 350 ms after the meteor was obscured for the second time behind foreground clouds, a well-formed and morphologically typical sprite appeared in the immediate vicinity of the meteor (Figures 1e–1g). The sprite spanned the 57 to 86 km altitude range and was partially obscured by clouds. The arrows in Figures 1e and 1f trace the trajectory of the meteor as shown in Figures 1a–1d, and the open circles at ~70 km altitude in Figures 1e and 1f indicate the position that the meteor would have attained at the onset of the sprite, assuming a constant apparent velocity and nonextinction after obscuration by clouds. Weak patches of blue emissions were also detected in one frame of the blue light video with a time stamp of 0444:56.245 UT. The brightness of the patches was at the limit of the camera sensitivity and covered the entire vertical extent of the sprite.

In the late stages of the sprite formation (Figures 1g and 1h) a slower upward propagating jet of luminosity was observed to follow the original path of the meteor. The propagation and definition of this jet are very obvious when viewed as video. The jet was observed to propagate from ~80 to 84 km in altitude before fading below the threshold of detectability. The initiation point of the jet may have been somewhat lower than 80 km and obscured by clouds. The jet had an apparent velocity (observed distance traveled by jet divided by observed total travel time of jet divided by cos 30°) of approximately (4 km)/(34–68 ms)/cos 30° ~67–134 km/s at the same 30° angle as the meteor and had an apparent width of no more than 1–2 km. The spread in the speed estimate is due to the timing uncertainty introduced by not knowing exactly when the jet appeared/disappeared during the 17 ms integration times of the video fields. Additionally, the speed estimate represents a lower bound since, again, the velocity component along the line of sight is unknown. Nonetheless, it is clear that the propagation speed of the jet is on the order of 100 km/s, similar to that of blue jets [*Wescott et al.*, 1995]. It should be pointed out that the description of this event as a "jet" is based solely on the similarity of its velocity to those of blue jets and does not necessarily imply an initiating mechanism similar to that of blue jets. No indication of the jet was seen in the blue light video or from broadband blue-filtered and red-filtered intensified cameras that were independently operated by Utah State University.

Figure 2 shows the time waveforms collected by the broadband red photometer (Figure 2a), and the 6° FOV 430 and 399 nm photometers (Figure 2b), and the VLF receiver (Figure 2c). The curve in Figure 2a is raw data while those in Figure 2b are noise filtered with a weighted-least-squares averaging. The averaging was necessitated by the relatively weak and noisy "blue" signals that were a consequence of the large line-of-sight distance [*Armstrong et al.*, 1998; *Suszcynsky et al.*, 1998]. The entire sprite and jet were in the FOVs of all photometers. The records were obtained simultaneously and began ~10 ms before the 0444:56.228 UT initiation of the sprite and ~350 ms after the last sighting of the meteor. The light curves have a risetime of ~1 ms, and the blue curves have a longer than typical decay time of ~15–20 ms. No VLF signature appeared during the sprite or for the recorded 10 ms prior to the sprite. National Lightning Detection Network (NLDN) data, including sensor data (V. Cummins and J. Cramer, Global Atmospherics Inc., private communication, 1998), produced only one candidate for the parent discharge. This was a positive CG discharge (24 kA peak current) that occurred at an azimuth of 105° and range of 382 km at 0444:56.106 UT, ~122 ms prior to the onset of the sprite and in agreement with the observed sprite azimuth. The only storm activity in the 0 to 1000 km range for the 105° azimuth was a N-S squall line in western Nebraska and Kansas. The center of the trailing stratiform region of this activity along the line of sight was at ~380 ± 50 km in agreement with the NLDN-reported event. Since sprites are strongly correlated with positive CG discharges, we assume that this positive CG discharge event was associated with the observed sprite. Consequently, its range was used to calculate the altitude scales in Figures 1f and 1g.

Table 1 summarizes the times and calculated altitudes associated with the various features of the described event. The times in Table 1 were determined by viewing the video one field at a time. The time listed for each field represents the start time of the 17 ms integration period. Altitudes were calculated by assuming an event range of 380 km and correspond to the altitude scale in Figures 1f and 1g.

3. Discussion

The possibility that meteors may trigger sprites has been postulated by *Muller* [1995]. *Muller* [1995] points out that the visually observed flux of ionizing meteors in nonshower conditions is $\sim 8 \times 10^{-7}$/km^2/s [*Allen*, 1973] and that this flux is comparable to the observed occurrence rate of 1×10^{-6}/km^2/s for sprites [*Sentman and Wescott*, 1993]. However, despite ground-based and aircraft-based observations of what is estimated to be on the order of 10^4 sprites over the last 10 years, the event described in this paper represents the only actual observation of a meteor in temporal and spatial coincidence with a sprite. An immediate conclusion from this data, then, is that even if a causal meteor-sprite mechanism can be shown to exist, it must be either very rare or typically initiated by subvisual meteors. Whatever the case may be, the event described in this paper represents a unique opportunity not only to explore the possibility of a causal relationship between a meteor and a sprite but also, more generally, to observe the effect of inserting a volume of ionization into the immediate electrical environment above a sprite-producing discharge.

With these initial comments in mind, three questions can be used to govern the analysis of the event: (1) To what extent did the meteor influence the development of the ensuing sprite/jet event, (2) assuming a causal relationship between the meteor and the sprite/jet event, what physical mechanisms were involved, and (3) what are the implications of the event for existing theories of sprite and jet development?

To address the first question, we can refer to the basic picture of a single thundercloud discharge and how it influences the electric field in the mesospheric region above it. Prior to a CG discharge, a strong electric field produced by

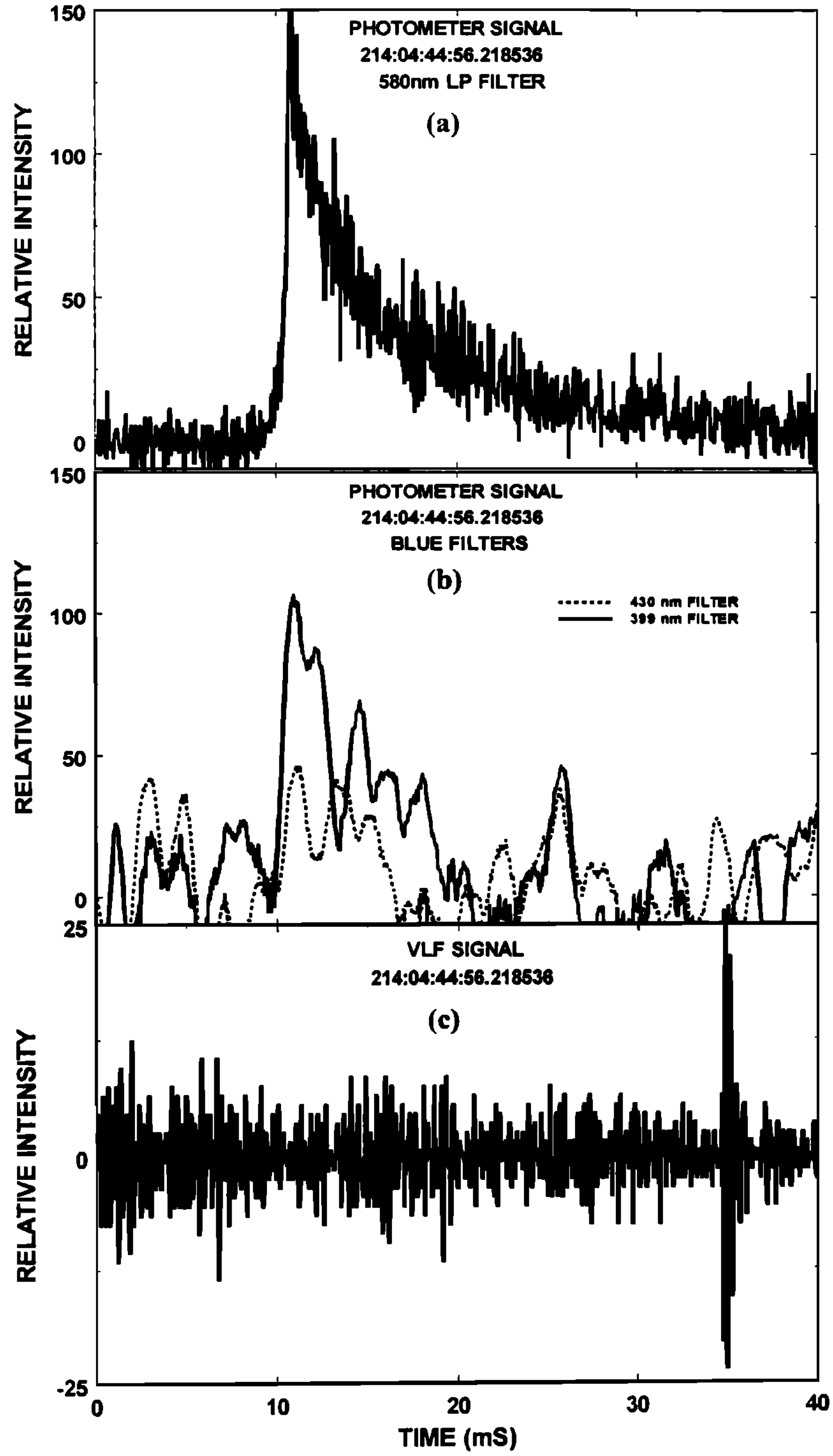

Figure 2. (a) Raw data light curves from the 580–900 nm photometer, (b) processed light curves from the narrowband 430 and 399 nm photometers, and (c) VLF trace for the event shown in Figure 1. LP filter, low-pass filter.

charge separation exists in the thundercloud. The mesospheric region above the cloud is field-free via a screening polarization charge layer that exists at the top of the cloud. When a CG discharge occurs, the electric field inside the cloud is neutralized, leaving the polarization charge and a quasi-static electric field in the mesosphere which subsequently produces a sprite presumably via one of the current theories for sprite production. In this picture a meteor might "trigger" the sprite by one of three mechanisms: (1) It perturbs the charge/electric field distribution inside the thundercloud to the extent that it initiates a CG discharge; this discharge then produces a sprite for reasons unrelated to the meteor. (2) It initiates the discharge as in mechanism 1 and also produces or enhances conditions that result in the production of a sprite. (3) It perturbs an electric field distribution at mesospheric altitudes in a way that results in the production of a sprite as a CG coincidentally occurs in temporal and spatial proximity to the meteor.

If the meteor triggered the parent CG discharge, the ionization trail of the meteor, which can be thought of as a conducting wire, would had to have entered the electric field region of the thundercloud. Assuming that the meteor continued on a constant apparent velocity trajectory once it became obscured by foreground clouds and assuming that it did not dissipate before the sprite appeared, it clearly would have traveled to no lower than ~70 km altitude at the onset of the sprite (Figures 1e and 1f). Consequently, it could not have triggered the CG since it was still well above the local cloud tops, below which it would need to reach in order to influence the prebreakdown electric field structure of the thundercloud.

It is also difficult to propose a mechanism for the meteor to trigger the sprite at mesospheric altitudes since the relaxation time at 70 km is only ~10 ms. Any electric field generated by the associated positive CG discharge at this altitude would dissipate on this timescale, and breakdown would occur an order of magnitude faster than the observed 122 ms delay between the parent CG and the sprite onset. If such a triggering does occur, there would need to be some process that maintains the quasi-electrostatic field for 122 ms or provides an enhanced field at sprite onset. A rapid enhancement in the mesospheric electric field caused by a sudden increase in the current to ground during a continuing current phase of the positive stroke might provide this driver. However, we have no observational evidence that suggests the presence of continuing current during this event.

Except for the relatively slow decay of the blue photometry signals with respect to the broadband red photometry signal, there was nothing unusual or exceptional about the size, geometry, altitude extent, features, or energetics of the sprite that might suggest an unusual generation mechanism. The 399 to 430 nm filter emission intensity ratio was ~2 (Figure 2b), which is typical for sprites [*Armstrong et al.*, 1998], and three other sprites of similar characteristics and location were observed within 15 min before and after the event.

The likelihood that a sporadic meteor trajectory would coincidentally intersect a sprite volume in the hundreds of milliseconds prior to the sprite can be calculated by using the sporadic meteor flux quoted by *Muller* [1995]. For a sprite with dimensions of those shown in Figure 1 (horizontal cross-sectional area of ~175 km^2) one would expect about (8×10^{-7} 1/km^2/s) (1 s) (175 km^2) ~10^{-4} sporadic meteors to intersect a sprite volume in a 1 s interval prior to the visual observation of that sprite. In other words, one would expect to observe about one sporadic and causally unrelated meteor in spatial and temporal coincidence with a sprite for every 10^4 sprites observed.

On the other hand, we cannot completely rule out the possibility of a meteor-sprite trigger scenario, particularly since there has been recent evidence [*Stanley et al.*, 1999] that sprites may initiate in the same 70–80 km altitude range where the meteor terminated. Additionally, the candidate parent positive CG discharge occurred 122 ms before the sprite onset; parent CGs typically occur on the order of 1–10 ms prior to sprite onset. Although such a time delay is not unprecedented, it may suggest an atypical electrical environment prior to the sprite. However, since it remains unclear how such a triggering mechanism can be implemented, we must conclude for this analysis that any causal relationship between the meteor and the sprite is conjectural at this time.

Table 1. Time and Altitude History of the Features Comprising the Described Event

Feature	Start Time of Field, UT	Altitude Estimates
First field of meteor	0444:54.794	100 km
Meteor enters cloud 1	0444:55.628	82 km
Meteor emerges from cloud 1	0444:55.779	78 km
Meteor enters cloud 2	0444:55.862	75 km
First field of sprite	0444:56.213	upper edge: 81 km lower edge: 57 km
Second field of sprite, brightest	0444:56.229	upper edge: 86 km lower edge: 57 km
Third field of sprite, brightness diminishes	0444:56.246	upper edge: 86 km lower edge: 57 km
Fourth field of sprite, first field of jet	0444:56.262	sprite: remnant patches jet: 80 km
Second field of jet	0444:56.279	82 km
Third field of jet	0444:56.296	83 km
Fourth field of jet, event ends	0444:56.313	84 km

All times represent the start time of the 17 ms field integration containing the feature. All altitudes are based on an assumed event range of 380 km.

In contrast, the observation of the jet of luminosity that propagates back up the trajectory of the meteor is almost certainly associated with the presence of the meteor's ionization trail. Small jets of luminosity associated with the late stages of sprites similar to that described in this paper have been observed by *Stanley et al.*, [1996] and were interpreted to be associated with regions of sprite-produced ionization. The triggering of a similar event by the injection of meteoric ionization into the vicinity of a sprite would seem to support this interpretation.

Meteors produce ionization through inelastic collisions between their vaporized atoms and the surrounding air molecules. The amount of ionization is significant and can be estimated by considering the brightness of the meteor. The zenith-corrected magnitude M_z of a third-magnitude meteor observed at a 380 km range is ~0.0 [e.g., *Lovell*, 1954]. This brightness can be related to the number of electrons per meter produced through ionization, q, by $M_z = 36 - 2.5 (\log q - \log V_m)$, where V_m is the speed of the meteor in kilometers per second [*McKinley*, 1961]. For $M = 0.0$ and $V_m = 27$ km/s we estimate the ionization produced by the meteor to be on the order of 10^{16} el/m. The initial width of a 0.0-magnitude meteor ionization trail at the observed altitudes is typically on the order of 1 m in diameter [*Hawkins and Whipple*, 1958]. By way of expansion driven by ambipolar diffusion, recombination, and turbulence, the ionization trail can grow up to on the order of 1 km in diameter over a period of seconds to minutes.

The observed jet velocity is on the order of the local electron drift velocity [*Ali*, 1986] and is much too slow to suggest luminosity produced by a pure propagation of current up a fully ionized channel. Instead, the relatively slow speed implies a more complicated generation mechanism.

There are interesting similarities between the jet event and the normal evolution of optical emissions generated in the train of a meteor that may eventually help to define this generation mechanism. *Ceplecha et al.* [1998] point out that the optical radiation from meteor trains with duration up to 3 s and associated with faint and fast meteors is generally produced by the forbidden auroral line of neutral oxygen at 557.7 nm. They also note that the line starts to radiate following some delay after the meteor passage. The radiative lifetime of the O I (^{1}S) 557.7 nm line is ~750 ms, while the excitation process is most probably a dissociative recombination of O_2^+ leaving one of the oxygen atoms in the ^{1}S state. Assuming an ionization trail of 10^{16} el/m in a cross-sectional area of 5 m^2 at 80 km altitude, an efficiency of 10% for the production of O I (^{1}S) [see *Omholt*, 1971], and a fast conversion of N_2^+ to O_2^+ by charge exchange, we would deduce a production rate of ~40/s. This rate is fast compared to the relaxation time of the green line; however, it also decreases as l/t, and our estimates of the electron density can be off by an order of magnitude. In addition, the lack of a jet signature in both the broadband blue and red imagery is consistent with an O I 557.7 nm emission. In any case, the observed delay between the excitation process (the meteor) and the jet may be related to these processes.

The apparent motion of the jet might be related to a combination of camera sensitivity, an increase in the production of O I (^{1}S) emission with a decrease in altitude, and a rapid change in the decay rate of the emissions as a function of altitude. According to *McKinley* [1961] the train intensity generally decreases exponentially with time. In the altitude range of interest (~80 km) the exponential decay constant can be approximated as $k = 1.8\ (84.2 - h)$ visual magnitudes/s, where h is the height in kilometers. Thus a particular contour of intensity would increase its height with time at an apparent speed given by

$$V = \left(\frac{1}{k}\frac{dk}{dh}\right)^{-1}\frac{1}{\Delta t}, \tag{1}$$

where Δt is taken to be the duration of the emissions. This decay, coupled with the increased production of O I (^{1}S) at lower altitudes, might account for the net upward propagation of the jet. At 80 km altitude and given a duration of 40 ms for the jet, we obtain an apparent speed of 105 km/s in good agreement with the measurements. From the quenching rate for the O I (^{1}S) state due to collisions with O_2 and with electrons and to the radiative lifetime, it is also possible to deduce a magnitude for the decay rate. At 80 km altitude and given a duration of 40 ms for the jet, we obtain an apparent speed of 105 km/s in good agreement with the measurements. From the quenching rate for the O I (^{1}S) state due to collisions with O_2 and with electrons and to the radiative lifetime, it is also possible to deduce a magnitude for the decay rate. At 80 km we find $k = 10$ visual magnitudes/s which is in rough agreement with a linear extrapolation of the *McKinley* [1961] curve.

In summary, at this point in the analysis the occurrence of the sprite and associated positive CG discharge in spatial and temporal proximity to the meteor cannot be conclusively shown to exhibit a causal relationship. The occurrence of the ensuing jet event is clearly related to the meteor's ionization trail, and although the initiating mechanism is not obvious, some similarities between these observations and previous meteor observations are apparent. The meteor-sprite-jet event has raised some important but as yet unanswered questions regarding the electrical processes that occur in the lower mesosphere during the formative stages of sprites. In particular, one is forced to question the role of meteors in preconditioning the upper atmospheric conductivity and its implications for development of high-altitude discharges.

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