AGU 2020 Poster Draft

19 Nov 2020
Hans Nielsen

Title: Analysis and modeling of sprite green ghosts
Authors: Hans Stenbaek-Nielsen[1], Thomas Ashcraft[2], Matthew McHarg[3], Jacob Harley[3]
Affiliations: 1: Univ. of Alaska Fairbanks, 2: Heliotown Observatory, 3: US Air Force Academy

**Abstract**

In 2019 sprite observations appeared on You-Tube showing green emissions in the top of some sprites and after the main sprite. The emissions were named green ghosts. We present here similar color camera observations made on 24 and 25 May 2020 from Lamy, NM. The recordings were made at 30 fps. The green ghost increased in brightness for 3 to 4 frames after the main 'jellyfish' sprite and decayed thereafter. The delayed green emissions are likely from atomic oxygen at 557.7 nm, the auroral green line, which is a forbidden atomic oxygen emission with a radiative life time of 0.7 s. In the atmosphere the emissions are affected by quenching and at the altitude of the green ghost the decay time constant is substantially less. We suggest that the green ghost is generated by super thermal electrons exciting ambient atomic oxygen (only 4.1 eV required). The electrons are energized by the large-scale sprite electric field, which initially caused the sprite, and decays over some time after the sprite. We present a simple model based on this idea. The model assumes an exponentially decaying sprite E-field and reproduces the observed delayed peak in the green emissions and the subsequent decay of the emissions.

## Introduction

In 2019 sprite observations by Hank Schyma "VIBRANT RED SPRITES Jets & Mysterious Ghosts" and by Paul M. Smith "Bright sprite lightning event with trolls and green tipped streamer afterglow" appeared on YouTube ( https://www.youtube.com/watch?v=15Rdfz1UPJk and https://www.youtube.com/watch?v=o1NlZZHboSY). The images showed green emissions in the top of some sprites lasting well after the main sprite. The emissions were named “Green Ghosts” by Hank Schyma, and it was speculated that the green emissions were 557.7 nm atomic oxygen emissions well known to be present in aurora and airglow.


Figure 1. Green emissions in the top of a sprite.

In early 2020 Dr. L. McDonald, who leads a “Citizen Scientist” program at NASA/GSFC, connected sprite observer Mr. T. Ashcraft with the University of Alaska Fairbanks/US Air Force Academy sprite research team. One of his sprite images with green emissions in the top is shown in Figure 1. On 24 and 25 May 2020 Mr. Ashcraft made two recordings of sprites with Green Ghosts and these recordings provide the data for this AGU 2020 poster.

## Data and Analysis

The two Green Ghost events were recorded at 30 fps on 24 and 25 May 2020 at Heliotown Observatory in Lamy, NM (35.5028N, -105.8936E) using a SONY A7s II in video mode. The sprite on 24 May 2020 was at 03:31:22 UT, and the sprite on 25 May 2020 was at 03:55:19 UT. In both events the green ghost appears in the top of a large sprite and lasts about a second after the sprite has turned off. The 24 May sprite has 24 frames (0.7 s) and the sprite on 25 May has 36 frames (1.2 s) with sprite and ghost features. The videos can be viewed at https://vimeo.com/422073242 (24 May 2020)and https://vimeo.com/423369251 (25 May 2020).

Figure 2 shows six frames from the 25 May 2020 event. The main sprite lasts 2 frames. After turn-off, t = 66 ms, a faint green ghost is present in the area of the top of the sprite. The ghost brightens reaching maximum at frame 8, t= 166 ms, and decays after that. The event on the previous day, 24 May 2020, was very similar.


Figure 2. Sprite with green ghost recorded 25 May 2020 at 30 fps (33 ms between mages). The green ghost reaches maximum intensity at t = 166 ms and decays after that.  The green in the green ghost images, images 2-6, has been enhanced.

For analysis images were extracted from the videos and RGB color components separated.  To analyze altitude variations we extracted pixel brightness integrated over 10 rectangular boxes covering the green ghost (Figure 3). The green ghost appears on top of a relatively high background which we subtracted. Both sprites were located southeast of Lamy, NM, and assuming the sprite to be over the causal lightning strike the altitude covered by the boxes varies from 97 km (box at the top) to 83 km (box at the bottom).

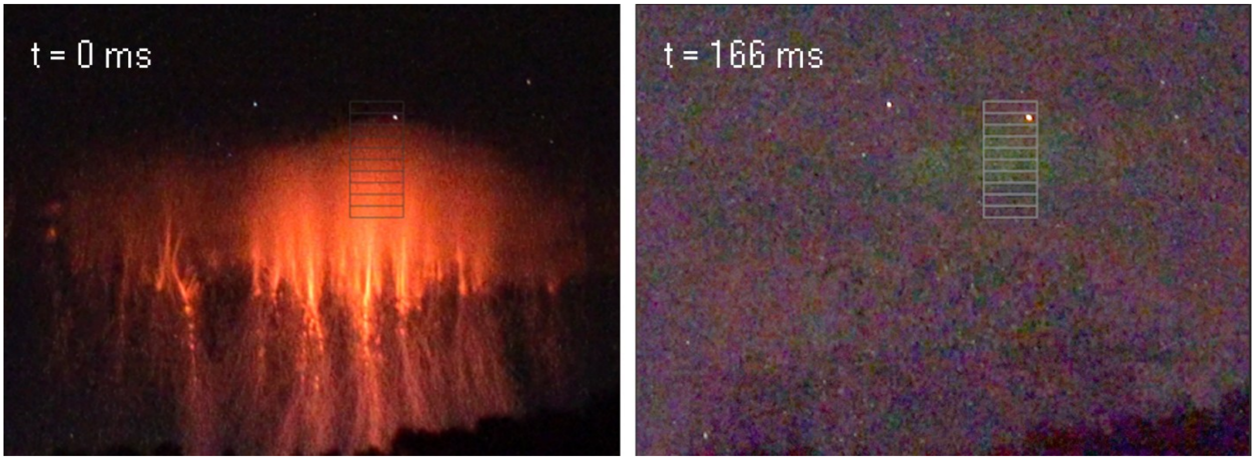


Figure 3. 25 May 2020: Location of the box array used for extracting the brightness variation of the green ghost.

A representative plot of the brightness variation from each of the two events is shown in Figure 4. In the first few frames the green signal is near saturation, but after the main sprite turns off, the green emission is seen to increase towards a maximum around frame 8 in the two sequences. After that it decreases and an exponential has been fitted to the time series. We assume that the green ghost is from atomic oxygen emission at 557.7 nm, an emission that is well known in aurora and airglow. It is a forbidden emission with a radiative life-time of 0.7 s. Thus we would expect the emissions to trail the main sprite and to decay exponentially, which is indeed the case.

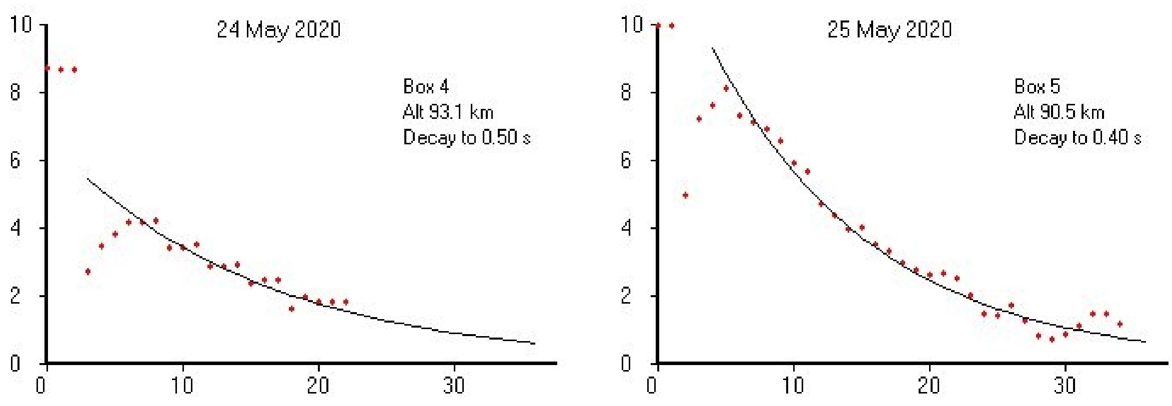


Figure 4. Plot of green emissions for box 4 (24 May 2020) and 5 (25 May 2020). The ordinate is in arbitrary units, and the abscissa in sequence frame number. An exponential has been fitted to the decay phase of the events. The decay time constant is given on the plots.

In the two events the main sprite lasts 2 and 3 frames respectively (60-100 ms) with little change. Based on our experience observing sprites with high-speed cameras most large sprites are rarely active for more than 30 ms, and we think there may be some instrumental issues related to the internal camera image processing and settings. We are looking into those issues.

The green atomic oxygen emission is affected by atmospheric quenching. Thus we would expect the decay time constant to be less that the 0.7 s radiative decay life time, and further, that the observed decay time constant should be smaller at lower altitudes because of the increasing atmospheric density. While the observed decay time constants are all less than 0.7 s, the time constant only decreases with lower altitude for the 24 May event. For the 25 May 2020 event we observe a time constant of 0.4 s for all altitudes. While the decay appears to be exponential, as expected, the observed time constants are larger than the expected 0.1 to 0.2 s based on equations and rate constants given by Vallance Jones (1974) in chapter 4.2. The observed maximum after the sprite has turned off and the decay time constant being larger than expected indicate that there are processes present following the main sprite leading to the green ghost.

**Main Points:**

- The analysis is for 2 events only, both large sprites (jellyfish)
- Generally green ghosts are relatively rare
- Altitude around 90-95 km; same altitude as the auroral green line (atomic oxygen)
- Ghost reaches peak intensity 50-120 ms after the sprite turn-off
- The observed exponential decay has a time constant 0.6 – 0.25 s; this is less than the 0.7 s value for the 557.7 nm atomic oxygen emission in vacuum, but higher than 0.2-0.1 s expected based on data in Vallance Jones (1974)
- The last two bullets suggest additional processes beyond the duration of the main sprite

## Green Ghost Model

With the assumption that the green ghost emissions are by the auroral green line at 557.7 nm, we can formulate a simple model. The 557.7 nm emission is a forbidden atomic oxygen emission with a radiative life-time of 0.7 s, and it is easy to excite (it only requires 4.2 eV). The long radiative life time relative to the camera exposure time, 33 ms, means that if an energy source is turned on, the emission will be observed to rise gradually towards a steady state rate, and conversely, if the source is turned off, the emission will decay with the same time constant.

Sprites occur in the atmosphere and quenching through collisions with atmospheric constituents adds an additional process for deactivating excited atoms. The net effect is that the time constant associated with the emission is lower than 0.7 s. Vallance Jones (1974) has an extensive treatment of the processes affecting the green emission, including quenching, and all reaction rate constants are given there. The dominant quenching process is collision with O2 or O. In some references N2 and NO are mentioned as possibilities, but Vallance Jones discounts that. The associated quenching coefficients vary substantially. In particular the quenching rate for O is likely larger than the value quoted by Vallance Jones (Slanger and Black, 1981), but this will not qualitatively change the model results.

A sprite is caused by an electric field set up by a lightning strike, and it decays on varying time scales as evidenced by the duration of the sprite optical emissions; some sprites last less than 10 ms and other have optical emissions lasting up to about 100 ms. With a decaying background electric field capable of exciting atomic oxygen and the 0.7 s radiative life time of atomic oxygen we have the basic elements for a model.

We use the formulation, parameter designations, and constants given by Vallance Jones (1974) in section 4.2 to calculate the 557.7 nm emission rate.

Let n be the number of exited oxygen atoms, then the 557.7 emission rate I5577 is:

$$I5577 = A32 * n \qquad (1)$$

where A32 is the radiative probability.

The rate of change in n is given by:

$$dn/dt = s(t) - ( A + d3 ) * n \qquad (2)$$

Here s(t) is the rate at which oxygen atoms are excited and (A + d3) are the losses; A is the radiative losses and d3 the quenching losses.

The energy state leading to the 557.7 emission is the O(1S) state which decays into either the O(1P) state or the ground-state O(3P) with the probabilities A32 and A31 respectively. Thus:

$$A = A32 + A31 \qquad (3)$$

The quenching loss rate, d3, is for quenching with O and O2:

$$d3 = k3 * [O2] + k4 * [O] \qquad (4)$$

where k3 and k4 are the rate constants and [O2] and [O] the altitude dependent atmospheric densities.

The values of the parameters A32, A31, k3, and k4 are given by Vallance Jones (1974):

A32 = 1.28 /s
A31 = 0.078 /s
k3 = 3E-13 cm3/s
k4 = 7.5E-12 cm3/s

The atmospheric densities [O2] and [O] are from the MSIS-E-90 Atmosphere Model provided by NASA/GSFC here (https://ccmc.gsfc.nasa.gov/modelweb/models/msis_vitmo.php). At an altitude of 95 km MSIS gives:

[O2] = 4.553E+12 /cm3
[O] = 2.611E+11 /cm3

The excitation rate, s(t), of the atomic oxygen is associated with the sprite, and we will assume the excitation is through local free electrons energized by the sprite background electric field. We will further assume that the background Efiled is set up at sprite onset and then decays exponentially with a time constant of $t_{E0}$, and that the atomic oxygen excitation rate is proportional to the background electric field. The time dependent excitation rate, s(t), can then be formulated as:

$$s(t) = C \exp(t/t_{E0}) \qquad (5)$$

where C is the initial excitation value.

Our green ghost model is now defined quantitatively. The values C and $t_{E0}$ are 'free' parameters used to fit model prediction with observations.

## Modelling Results

The green ghost is mainly in box 3-7 for the 24 May 2020 sprite, and box 3 – 8 for the 25 May 2020 sprite. Model fits for the two events are shown below in Figures 5 and 6.

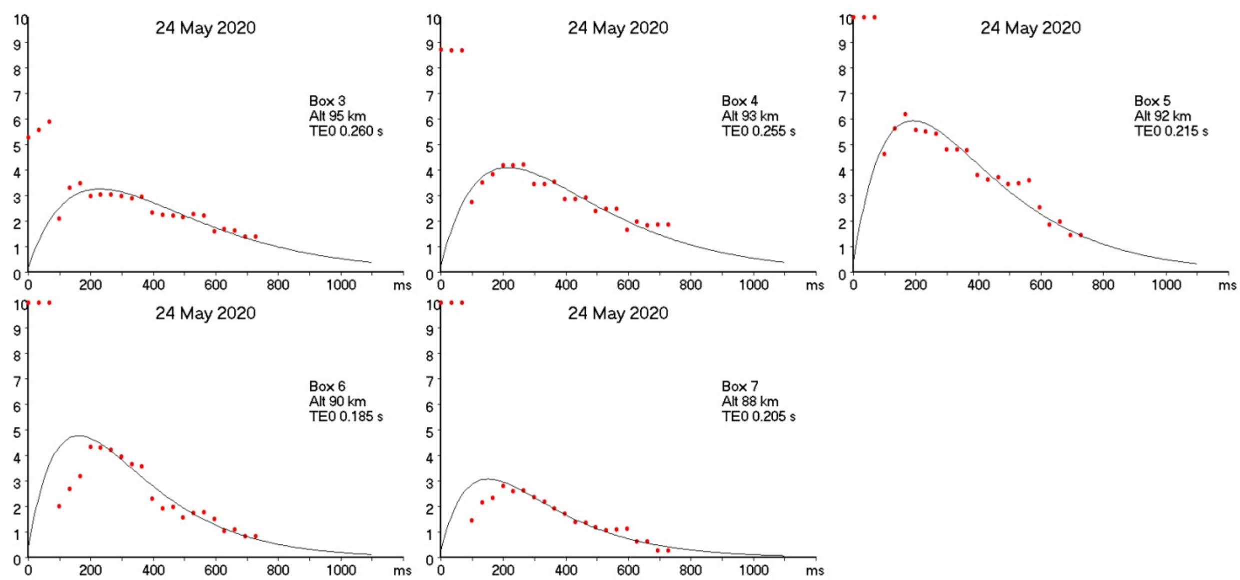


Figure 5. Observed green intensities and model fits for the 24 May 2020 green ghost sprite. The ordinate is in arbitrary units, and the abscissa is in ms from the onset of the sprite.

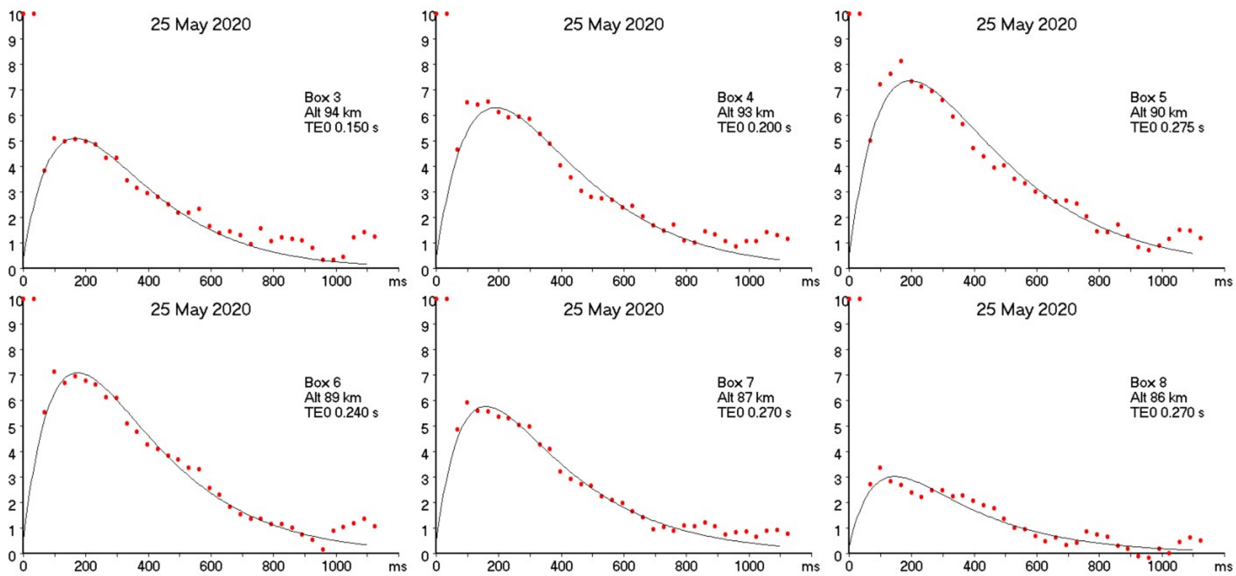


Figure 6. Observed green intensities and model fits for the 25 May 2020 green ghost sprite. The ordinate is in arbitrary units, and the abscissa is in ms from the onset of the sprite.

The proposed model for the green ghost fits the observations surprisingly well given its simplicity. The main fitting problem between model and observations is in box 6 and 7 of the 24 May 2020 event where the observed initial rise is later that the model predicts. There could be an issue with the background subtraction, or the assumed electric field might be established later at the lower altitude represented by box 6 and 7.

To allow some quantitative assessment of the analysis and model we list key parameters for the analysis of the two events:

24 May 2020:

| | | | | | |
|---|---|---|---|---|---|
| Box nr | 3 | 4 | 5 | 6 | 7 |
| Altitude [km] | 94.7 | 93.1 | 91.6 | 90.0 | 88.4 |
| Model parameters | | | | | |
| C | 29 | 39 | 63 | 59 | 41 |
| E-field $t_{E0}$ | 0.26 | 0.23 | 0.22 | 0.19 | 0.21 |
| Observed decay $t_0$ | 0.6 | 0.5 | 0.4 | 0.3 | 0.25 |
| Calculated $t_0$ | 0.21 | 0.19 | 0.18 | 0.15 | 0.12 |

25 May 2020:

| | | | | | | |
|---|---|---|---|---|---|---|
| Box nr | 3 | 4 | 5 | 6 | 7 | 8 |
| Altitude [km] | 93.5 | 92.9 | 90.5 | 88.9 | 87.4 | 85.9 |
| Model parameters | | | | | | |
| C | 61 | 67 | 77 | 83 | 75 | 43 |
| E-field $t_{E0}$ | 0.15 | 0.20 | 0.28 | 0.24 | 0.27 | 0.27 |
| Observed decay $t_0$ | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Calculated $t_0$ | 0.20 | 0.19 | 0.17 | 0.14 | 0.11 | 0.10 |

The electric field in the model provides the excitation leading to the green ghost 557.7 nm emissions. The time constant indicates how fast the field, and therefore the added excitation, decays. At any given time the excitation will add to the atomic oxygen state leading to the green emission. Therefore the observed decay time constant should be expected to be larger than the 'no added excitation' time constant calculated based on the equations and rate constant given by Vallance Jones (1974). This 'no added excitation' time constant is listed in the line Calculated $t_0$, and it is indeed less than the observed time constant on the line above. For the 25 May 2020 event the observed decay rate is a constant 0.40 s for all boxes. The altitude is decreasing from 93.5 km (box 3) to 85.9 km (box 8) and with the denser atmosphere at lower altitudes the effect of quenching will increase which will lower the 'no added excitation' time constant as seen in the line "Calculated $t_0$". The model E-field must then make up the difference and we see this in the increase of the E-field decay time constant between box 3 and 8.

There is uncertainty on the parameters involved in the analysis. We have assumed that the sprites are above the location of the lightning strike, but sprites may be several 10s of km from the strike (a review of this is given in Stenbaek-Nielsen et al. (2020)). A reasonable uncertainty on the altitude would be 5 km. A change in altitude will seriously affect the quenching and therefore the expected decay time constant. Another set of uncertainties is associated with the rate constants used when calculating the decay time constant, especially the atomic oxygen quenching rate constant. This rate constant may be significantly larger than given by Vallance Jones (1974). The uncertainties will affect the model fit, however, the uncertainties do not appear to affect the overall qualitative results of the analysis presented here.

## Conclusion

We have presented a model for the sprite green ghost based on the emissions being the auroral green line at 557.7 nm and an assumed lightning associated electric field decaying exponentially. The model can fit the observations of a two green ghosts made 24 and 25 May 2020 from Lamy, NM, lending support to the suggestion that the emissions are indeed from atomic oxygen. The observation that the green ghost has maximum intensity well after the main sprite has turned off combined with the observed green emission decay time constant being significantly larger than time constants calculated based on formulas and rate constants given by Vallance Jones (1974) indicate the presence of processes lasting well after the main sprite has turned off.

## Acknowledgments

We thank Hank Schyma and Paul M. Smith for use of their videos. We also thank B. Kosar for valuable discussions.

## References

Slanger, T. G., and G. Black, Quenching of O(1S) by O2(a1Δg) (1981), Geophysical Research Letters, 8, 535

Stenbaek−Nielsen, H. C., M. G. McHarg, R. Haaland, and A. Luque (2020), Optical Spectra of Small−Scale Sprite Features Observed at 10,000 fps, Journal of Geophysical Research – Atmospheres, 125, 20, doi.org/10.1029/2020JD033170

Vallance Jones, A. (1974), Aurora, D. Reidel, Dordrecht, Netherlands. https://doi.org/10.1007/978-94-010-2099-2