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Supplementary information

Observation of the onset of a blue jet into the stratosphere

In the format provided by the authors and unedited

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Peer Review File

Manuscript Title: Observation of the onset of a blue jet into the stratosphere

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

The paper by Neubert et al shows very interesting data about blue discharges at the tops of thunderstorms. It has long been known that tropical thunderstorms produce a large number of negative narrow bipolar events (-NBEs) at high altitudes. The Neubert paper shows that a tropical thunderstorm produces a large number of blue flashes with characteristics consistent with -NBEs which strongly suggest that the blue flashes are the optical manifestations of -NBEs. It has recently been shown that positive NBEs at mid-level altitudes in thunderstorms sometimes initiate intra-cloud (and bolt-from-the-blue type cloud-to-ground) lightning flashes, and low-altitude negative NBEs sometimes initiate normal cloud-to-ground lightning flashes. The Newbert paper shows that, in one instance, a blue flash initiates a blue jet, suggesting that high-altitude -NBEs initiate longer-lasting discharges just as lower altitude NBEs do. They also show that the blue flashes have very small emissions in the red spectral band indicating that the blue flashes are most likely cold streamer discharges rather than discharges which have hot leader channels. They also show convincingly that at least one of the blue flashes initiates an elve. As far as I know this is the first observation showing an elve initiated by something other than a full-fledged lightning discharge. The weakest part of the paper is that it does not more strongly tie together the blue flashes with -NBEs -- there are no simultaneous measurements of -NBE electromagnetic signatures with the blue flashes. A recent paper from Soler et al (doi 10.1029/2020JD032708) shows that, in a different tropical thunderstorm, ASIM-detected blue flashes did indeed have the electromagnetic signatures of -NBEs. I am surprised that the Neubert paper does not reference the Soler paper since several of the authors of both papers overlap.

The Neubert paper shows that blue flashes have rise times and durations consistent with -NBEs (10-20 μs). The blue photometer measurements show that the flashes emit blue spectral radiation for tens of milliseconds after the initial higer-power pulse. These blue emissions are probably due to continued streamer propagation after the parent -NBE. Perhaps it is beyond the scope of the article but it would be interesting to know if this later streamer development would produce detectable electromagnetic signatures, and if historical observations of -NBEs show a tail which could be due to this development.

Overall the paper is well written and needs little modification if it is published. I found just a few errors or typos in the paper:

On line 273, the authors state that a lightning flash with a -126 kA generated an elve, whereas on line 114 and in Extended Data Table 1 the current is listed as -123 kA.

One lines 172-173, the name of the journal is omitted in the reference.

I don't understand the difference between t-source and t-asim for the elve and the blue flashes in Extended Data Table 1. The t-source for the lightning strokes is from GLD360. What is t-source for the evle and blue flashes? I assume the authors use the GLD360 times of the 22 GLD360-detected lightning strokes and the ASIM photometer measurements to get the offset of the ASIM clock. Is t-asim the time of the peak photometer signal on the blue photometer on the corrected ASIM clock? If so, what is t-source? Why is t-asim sometimes earlier than t-source and sometimes later than t-

source?

Overall I find the paper to be highly interesting, showing that blue flashes at the tops of thunderstorms are quite common, that they have timing characteristics consistent the -NBEs, that they sometimes lead to larger discharges analogous to the way lower-altitude NBEs sometimes lead to full-fledged lightning flashes, and blue flashes can have currents large enough to produce elves. I would recommend publication after small modifications.

Referee #2 (Remarks to the Author):

The authors present their recordings of 5 lightning events (3 of them in the main paper) obtained using three photometers (operating in the blue, red, and UV ranges) and two framing cameras (operating in the blue and red ranges). The instruments are part of the ASIM installed on the International Space Station. The presented data correspond to the so-called blue flashes one of which initiated a blue jet extending from the cloud top to the stratosphere. The data are unique and definitely worth of publication. Below are my specific comments on the paper content and presentation.

1. The paper is titled "The genesis of blue lightning into the stratosphere". In my opinion, this title does not accurately represent the main paper content and is potentially confusing. What the authors call "blue lightning into the stratosphere" is commonly referred to as "blue jet" (also "blue starter" or "gigantic jet", depending on its vertical extent), and it may be just the above-cloud part of ordinary lightning occurring inside the cloud. It would be better to replace "blue lightning" with "blue jets" or "blue discharges". Further, the term "genesis" seems to be unjustified. The authors just "conjecture" (see line 152) that their observed blue flashes are optical manifestations of the so-called narrow bipolar events (NBEs), but do not present the corresponding NBE signatures to confirm that claim. Note that NBE signatures could potentially be recorded by GLD 360.
2. The Abstract should be better organized. For example, gigantic jets are discussed in the paper, but totally missing from the list of blue discharges given in lines 10-12 of the Abstract. Further, as many as 7 references are given in the 15-line Abstract, which is unusual (in my opinion, new science should be emphasized in the Abstract). In lines 17-18, it sounds like an optical (blue) flash "radiates radio waves". Please clarify. I recommend the whole sentence in lines 20-22 be rewritten, because it seems to imply that the authors have established that NBEs (not presented in this paper) are associated with the onset of blue lightning. In reality, they only inferred that their observed blue flashes are optical manifestations of NBEs.
3. Referencing prior works in some places appears to be kind of random to me. Sometimes modeling papers are referred to when observational evidence is expected (e.g., 5 in line 18 and 26 in line 146). Secondary publications are often cited instead of primary ones (e.g., 8 should be replaced with 19 in line 29). Some pertinent references are missing. Blue starters were first reported by Wescott et al. (1996) and gigantic jets by Pasko et al. (2002).
4. The authors recorded a faint signal in the red band and interpreted it as evidence of a "small [short?] and short-lived leader element" (see lines 61-64; also line 84 and lines 135-136). Is it possible that the "leader element" is just located deeper in the cloud? Is it associated with NBE, which the authors inferred to be a RF companion of blue flash?
5. Lines 140-155 are devoted to possible association of blue flashes with NBEs. Here, the authors introduce another name for NBEs: Compact Intracloud Discharges (CIDs), which should be done earlier in the paper and using primary references (e.g., Smith et al, 1999; Nag et al., 2010). Association of blue discharges with NBEs/CIDs was recently discussed by Leal and Rakov (2019), a pertinent reference missing from the paper:

"It appears that CIDs can initiate (or lead to the initiation of) not only normal lightning, but also the so-called
transient luminous events (TLEs) developing from clouds toward the ionosphere, which include blue starters,

blue jets, and gigantic jets. Specifically, lower-level CIDs (occurring between the main negative and main positive
charge regions) were reported to precede gigantic jets by some hundreds of milliseconds45–47. More recently,
Chou et al.48 observed 6 "blue luminous events" that were accompanied by upper-level CIDs, occurring between
the main positive and screening negative charge regions, at heights ranging from 16 to 18 km above ground level.
Similarly, Liu et al.49 reported on 6 "blue discharges" each occurring within 1 ms (their time uncertainty) after an upper-level CID occurring at a height in the 15 to 18 km range above ground level. Interestingly, while upper-level CIDs appear to directly initiate upward-jet-type events, lower-level CIDs do so via normal ICs lasting some hundreds of milliseconds."

6. In line 141, the authors define NBEs as "bipolar pulses in radio signals observed at HF/VHF". This is incorrect. NBEs are LF (30-300 kHz) pulses accompanied by HF/VHF (3-300 MHz) radiation bursts.

Overall, this is a great paper, which should be published as soon as possible.

References

Leal, A. and V.A. Rakov, A study of the context in which compact intracloud discharges occur, Sci. Rep., 2019, 9:12218, https://doi.org/10.1038/s41598-019-48680-6.

Nag, A., V. A. Rakov, D. Tsalikis, and J. A. Cramer (2010), On phenomenology of compact intracloud lightning discharges, J. Geophys. Res., 115, D14115, doi:10.1029/2009JD012957.

Pasko, V. P., Stanley, M. A., Mathews, J. D., Inan, U. S. & Wood, T. G. Electrical discharge from a thundercloud top to the lower ionosphere, Nature 416, 152–154 (2002).

Smith, D. A., X. M. Shao, D. N. Holden, C. T. Rhodes, M. Brook, P. R. Krehbiel, M. Stanley, W. Rison, and R. J. Thomas (1999), A distinct class of isolated intracloud discharges and their associated radio emissions, J. Geophys. Res., 104, 4189–4212.

Wescott, E.M., Sentman, D.D., Heavner, M.J., Osborne, D.L., and Vaughan, O.H. 1996. Blue starters: Brief upward discharges from an intense Arkansas thunderstorm. Geophys. Res. Lett. 23: 2153-6.

Author Rebuttals to Initial Comments:

The genesis of blue lightning into the stratosphere, by Torsten Neubert et al.

We thank the reviewers for their constructive remarks, which will improve the paper. Our response and modifications are described below.

Response to reviewer 1:

The paper by Neubert et al shows very interesting data about blue discharges at the tops of thunderstorms. It has long been known that tropical thunderstorms produce a large number of negative narrow bipolar events (-NBEs) at high altitudes. The Neubert paper shows that a tropical thunderstorm produces a large number of blue flashes with characteristics consistent with -NBEs which strongly suggest that the blue flashes are the optical manifestations of -NBEs. It has recently been shown that positive NBEs at mid-level altitudes in thunderstorms sometimes initiate intra-cloud (and bolt-from-the-blue type

cloud-to-ground) lightning flashes, and low- altitude negative NBEs sometimes initiate normal cloud-to-ground lightning flashes.

> Thank you for the information on low-altitude -NBE. We have modified the wording a little bit in the last section where we discuss NBE, to reflect that sources of -NBEs are not only at the top of clouds but also can be located at low altitudes.

The Neubert paper shows that, in one instance, a blue flash initiates a blue jet, suggesting that high-altitude -NBEs initiate longer-lasting discharges just as lower altitude NBEs do. They also show that the blue flashes have very small emissions in the red spectral band indicating that the blue flashes are most likely cold streamer discharges rather than discharges which have hot leader channels. They also show convincingly that at least one of the blue flashes initiates an elve. As far as I know this is the first observation showing an elve initiated by something other than a full-fledged lightning discharge.

The weakest part of the paper is that it does not more strongly tie together the blue flashes with - NBEs -- there are no simultaneous measurements of -NBE electromagnetic signatures with the blue flashes.

> Yes, unfortunately we have found no electromagnetic data simultaneously with our observations. So, we are left with the conjecture in the last paragraphs.

A recent paper from Soler et al (doi 10.1029/2020JD032708) shows that, in a different tropical thunderstorm, ASIM-detected blue flashes did indeed have the electromagnetic signatures of - NBEs. I am surprised that the Neubert paper does not reference the Soler paper since several of the authors of both papers overlap.

> The Soler et al. paper has now been published and we can reference it. It did not report on - NBEs but on +NBEs. We have reorganized the last paragraph, reference the paper, and clarify the differences of the polarity of NBEs.

The Neubert paper shows that blue flashes have rise times and durations consistent with - NBEs (10-20 μs). The blue photometer measurements show that the flashes emit blue spectral radiation for tens of milliseconds after the initial higher-power pulse. These blue emissions are probably due to continued streamer propagation after the parent -NBE. Perhaps it is beyond the scope of the article but it would be interesting to know if this later streamer development would produce detectable electromagnetic signatures, and if historical observations of -NBEs show a tail which could be due to this development.

> We agree that it is outside the scope of the paper. But we thank the reviewer for the suggestion. We are searching for ASIM observations of these blue flashes within range of receivers, but so far without luck. Historical data search sounds interesting. We hope that someone who is expert in such data will try this…it does take an expert.

On line 273, the authors state that a lightning flash with a -126 kA generated an elve, whereas on line 114 and in Extended Data Table 1 the current is listed as -123 kA.

> Corrected.

One lines 172-173, the name of the journal is omitted in the reference.

Corrected.

I don't understand the difference between t-source and t-asim for the elve and the blue flashes in Extended Data Table 1. The t-source for the lightning strokes is from GLD360. What is t-source for the elve and blue flashes? I assume the authors use the GLD360 times of the 22 GLD360- detected lightning strokes and the ASIM photometer measurements to get the offset of the ASIM clock. Is t-asim the time of the peak photometer signal on the blue photometer on the corrected ASIM clock? If so, what is t-source? Why is t-asim sometimes earlier than t-source and sometimes later than t-source?

Yes, t-asim is the time of the corrected clock. The clock is set by aligning the elve and the corresponding UV pulse. So, they are the same for this event. t-source accounts for changes in the propagation delay relative to the elve event. Changes have two origins.
One is that the source of lightning is consider at the Earth's surface, whereas blue flashes are at the cloud tops. The other is that the distance to ISS changes as it flies over the cloud during the 100 sec of the observations.

We have clarified the explanation in the Methods section.

Overall, I find the paper to be highly interesting, showing that blue flashes at the tops of thunderstorms are quite common, that they have timing characteristics consistent the -NBEs, that they sometimes lead to larger discharges analogous to the way lower-altitude NBEs sometimes lead to full-fledged lightning flashes, and blue flashes can have currents large enough to produce elves. I would recommend publication after small modifications.

Response to reviewer 2:

The authors present their recordings of 5 lightning events (3 of them in the main paper) obtained using three photometers (operating in the blue, red, and UV ranges) and two framing cameras (operating in the blue and red ranges). The instruments are part of the ASIM installed on the International Space Station. The presented data correspond to the so-called blue flashes one of which initiated a blue jet extending from the cloud top to the stratosphere. The data are unique and definitely worth of publication. Below are my specific comments on the paper content and presentation.

1. The paper is titled "The genesis of blue lightning into the stratosphere". In my opinion, this title does not accurately represent the main paper content and is potentially confusing. What the authors call "blue lightning into the stratosphere" is commonly referred to as "blue jet" (also "blue starter" or "gigantic jet", depending on its vertical extent), and it may be just the above- cloud part of ordinary lightning occurring inside the cloud. It would be better to replace "blue lightning" with "blue jets" or "blue discharges". Further, the term "genesis" seems to be unjustified.

I never liked the term "blue jet", but I guess we now are stuck with it. We argue in

the paper that there is no electrical activity within the cloud before the blue flash. Thus, the blue jet starts with a big intensive blue flash at the cloud top. This is the whole point of the paper. Therefore, we think the word "genesis" is justified. Nevertheless, we propose the alternative title:

"Observation of the onset of a blue jet into the stratosphere"

The authors just "conjecture" (see line 152) that their observed blue flashes are optical manifestations of the so-called narrow bipolar events (NBEs), but do not present the corresponding NBE signatures to confirm that claim. Note that NBE signatures could potentially be recorded by GLD 360.

We have the GLD360 data, they are given in table Extended Data Table 1. They have no information on NBE occurrences. As discussed in our response to referee 1, we have identified no sources of data that would give us confirmation of NBE. We are searching, however, for other storms were data are available, as yet without luck.

2. The Abstract should be better organized. For example, gigantic jets are discussed in the paper, but totally missing from the list of blue discharges given in lines 10-12 of the Abstract.

We debated if to include a mention of gigantic jets in the abstract and decided against, as the paper focuses on the stratosphere and blue emissions. The upper portion of a gigantic jet is red and in the mesosphere. We have deleted references to gigantic jets everywhere in the paper to focus the message, and to adhere to limits on abstract length, paper length, number of references.

Further, as many as 7 references are given in the 15-line Abstract, which is unusual (in my opinion, new science should be emphasized in the Abstract).

We need references to give the background. The abstract has been rewritten following the reviewers and the Editors suggestions. We defer this point to the Editor.

In lines 17-18, it sounds like an optical (blue) flash "radiates radio waves". Please clarify.

The abstract has been reformulated. We hope it clarifies.

I recommend the whole sentence in lines 20-22 be rewritten, because it seems to imply that the authors have established that NBEs (not presented in this paper) are associated with the onset of blue lightning. In reality, they only inferred that their observed blue flashes are optical manifestations of NBEs.

We used the word "likely" to make it clear that we did not establish a direct connection to NBEs, but an indirect one. Again, the Editor also suggested some changes to the abstract, so it has been rewritten to accommodate the remarks by both the Editor and the reviewer.

3. Referencing prior works in some places appears to be kind of random to me. Sometimes modeling papers are referred to when observational evidence is expected (e.g., 5 in line 18 and 26 in line 146). Secondary publications are often cited instead of primary ones (e.g., 8 should be replaced with 19 in line 29). Some pertinent references are missing. Blue starters were first reported by Wescott et al. (1996) and gigantic jets by Pasko et al. (2002).

Our strategy of selecting references are
guided by: The requirement of a limit
of 30 references.
We attempt to reach readers that are not specialists in the field.

We chose papers that explain both observations, theory and modelling. They have long lists of references to observations. A reader outside the field may appreciate this.
Reference 8 is a primary paper often referenced, but it is a hard read. Reference 19 is much more accessible and gives a good review. Again, for readers outside the field. We would most certainly have referenced these papers in, for instance, JGR or GRL with unlimited number of references. Nevertheless, we may have gone overboard in our attempt to select easier references. We now include two additional primary references.

4. The authors recorded a faint signal in the red band and interpreted it as evidence of a "small [short?] and short-lived leader element" (see lines 61-64; also line 84 and lines 135-136). Is it possible that the "leader element" is just located deeper in the cloud? Is it associated with NBE, which the authors inferred to be a RF companion of blue flash?

"A faint signal suggests that a small and short-lived leader element is formed."
The sentence related to Fig. 2 and has been removed. The point is better made with Fig. 3, where it is already included.

5. Lines 140-155 are devoted to possible association of blue flashes with NBEs. Here, the authors introduce another name for NBEs: Compact Intracloud Discharges (CIDs), which should be done earlier in the paper and using primary references (e.g., Smith et al, 1999; Nag et al., 2010). Association of blue discharges with NBEs/CIDs was recently discussed by Leal and Rakov (2019), a pertinent reference missing from the paper:

"It appears that CIDs can initiate (or lead to the initiation of) not only normal lightning, but also the so-called transient luminous events (TLEs) developing from clouds toward the ionosphere, which include blue starters, blue jets, and gigantic jets. Specifically, lower-level CIDs (occurring between the main negative and main positive charge regions) were reported to precede gigantic jets by some hundreds of milliseconds45–47. More recently, Chou et al.48 observed 6 "blue luminous events" that were accompanied by upper-level CIDs, occurring between the main positive and screening negative charge regions, at heights ranging from 16 to 18 km above ground level. Similarly, Liu et al.49 reported on 6 "blue discharges" each occurring within 1 ms (their time uncertainty) after an upper-level CID occurring at a height in the 15 to 18 km range above ground level. Interestingly, while upper-level CIDs appear to directly initiate upward-jet- type events, lower-level CIDs do so via normal ICs lasting some hundreds of milliseconds."

Thank you for pointing this interesting paper out to us. We have included it. There is a general problem with CIDs vs NBEs. I see many papers that explain they essentially are the same process. CID is in a way a better name as it relates to a physical process, whereas NBE is the characteristic of an observed signal. However, we stay with NBE because of the recent papers linking blue emissions to NBEs, but we will refer to papers that go with CID, as we already did with the Rison paper.

6.In line 141, the authors define NBEs as "bipolar pulses in radio signals observed at HF/VHF". This is incorrect. NBEs are LF (30-300 kHz) pulses accompanied by HF/VHF (3-300 MHz) radiation bursts.

Thank you, corrected.

Overall, this is a great paper, which should be published as soon as possible.

We included the following references:

Proposed by reviewer:
Leal, A. and V.A. Rakov, A study of the context in which compact intracloud discharges occur, Sci. Rep., 2019, 9:12218, https://doi.org/10.1038/s41598-019-48680-6.

Proposed by reviewer:

Wescott, E.M., Sentman, D.D., Heavner, M.J., Osborne, D.L., and Vaughan, O.H. 1996. Blue starters: Brief upward discharges from an intense Arkansas thunderstorm. Geophys. Res. Lett. 23: 2153-6.

Original elve discovery paper instead of modelling paper:
Fukunishi, H., Takahashi, Y. and Kubota, M. Elves: Lightning-induced transient luminous events in the lower ionosphere, *Geophys. Res. Lett.* **23**, 2157– 2160 (1996).

Paper that now is published:
Soler, S., et al., Blue optical observations of narrow bipolar events by ASIM confirm streamer activity in thunderstorms. *J. Geophys. Res. Atm.*, **125**, e2020JD032708, DOI 10.1029/2020JD032708 (2020).

We took out:

Paper replaced by Winkler, 1996:
Edens, E. H. Photographic and lightning mapping observations of a blue starter above a New Mexico thunderstorm. *Geophys. Res. Lett*. **38**, L17804 (2011).

Paper replaced by Fukunishi, 1996:
Marshall, R. A. An improved model of the lightning electromagnetic field interaction with the *D*-region ionosphere. *J. Geophys Res.* **117**, A03316 (2012).

We rely on Mishin and Kreihbel papers:
Pasko, V. P. Blue jets and gigantic jets: transient luminous events between thunderstorm tops and the lower ionosphere. *Plasma Phys. Control. Fusion* **50**, 124050 (2008).

The submitted version had 29 references. The revised version has 30 references.