

Association of structured continuum emission with dynamic aurora

Corresponding Author: Dr Emma Spanswick

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The manuscript describes a previously known type of night sky emission in a previously unknown context. Analysis of this new conditions of what the authors call continuum emission in dynamic auroral display demonstrates coupling between the ionospheric plasma and neutral thermosphere processes. These observations are interesting to wider science community. However, the current version of the manuscript would benefit from some clarifications.

- The title could be more specific and more descriptive. Particularly the lens analogy can be misleading as the study uses sky cameras on the ground, which could literally incorporate new lens as new technology.
- The last paragraph of the manuscript refers to a large database from this study. However, 5 events are shown or mentioned in the manuscript, and the characteristics are given to their strongest event, which may or may not be representative. If many more events have been analyzed, that should be stated clearly, and the event description should include statements of common and different properties.

Minor notes:

- line 30: consider omitting "from certain sources". It does not add information.
- line 32: "another" instead of "one other"?
- line 53: "new lens" here makes the reader wonder if this is meant to be literally or figuratively..
- line 54: "narrow-band filtered cameras" should be rephrased to say that the cameras have narrow-band filters rather than that the cameras are somehow filtered.
- line 64, 65, 67, 82: It is unclear what is meant by "co-averaged frames", "color stability" and "color profiles". These terms are worth describing if there are no more descriptive ways of saying the same thing.
- line 75: "explores" rather than "explore"
- line 77: "images" rather than "imagers"
- line 81: If the audience is meant to be larger science community, things like "local light sources" should be explained too.
- line 90: Is the directional resolution an average of the whole view or precise in all/some directions? Can spectral resolution be given as well?
- line 113: Please provide a number or an order of magnitude for "shortly after".
- line 131: Is "4" meant to be a citation?
- line 143: The notation "OI" could be explained to help a wider audience to follow. Or alternatively consider not using that notation.
- line 175: What exactly is meant by "active auroras"?
- Chemical notation often lack the superscripts and subscripts which would make the text much more readable
- Emission line wavelengths could be typed in with the same number of digits throughout the manuscript

Reviewer #2

(Remarks to the Author)

The manuscript presents novel, groundbreaking observations of continuum emission in the aurora. Spectrograph observations of continuum emission in the aurora are rare, and concurrent imagery of 2-D auroral structure are unprecedented. This opens new windows of research into thermosphere-ionosphere coupling in the aurora, especially at mesoscales, and it may have important implications for other research areas like the continuum emission in STEVE.

The data and figures are presented clearly, the methodology is nearly flawless, and the conclusions are sound. I have no major comments, only some minor comments that I believe need to be addressed. But otherwise I suggest this be published promptly.

I have also included some optional suggestions, which the authors should feel free to ignore without comment.

Congratulations to the authors on a wonderful finding, a testament to the capability of the recently deployed TReX network.

MINOR COMMENTS

L32: "from the outer space": Be more specific.

L48: "consistent with" ... in what way? In terms of intensity, spectral shape, timing, or what parameter(s)?

Fig 2: Add information on the assumed emission height for the lat/lon labels.

Because the quantitative radiance is important, some more details are needed on calibration. For example, what is the accuracy or systematic uncertainty? Please add this or point to a paper that discusses it in detail.

L108: "Not visible to RGB imager": This gives the impression the RGB and imager disagree on the presence of aurora, but I don't think that's what you mean to imply. Perhaps: "Not visually apparent in the image when compared with the adjacent bright aurora", or "Not visually apparent without contrast adjustment"

Fig 3: For reproducibility, include the exact timestamps of the image. It says 11:17, but it's not clear if this is 1 image, or an average over the minute, etc. This is important information for readers to interpret the temporal alignment of the two datasets. Include this information both for the RGB camera and the spectrograph.

Fig 4 caption: The colors appear to be listed wrong. I think (red) should be (orange) and (black) should be (blue)? Please check. Also "orange diamonds" should be "green diamonds."

Fig 4: It's troublesome to treat the orange box as the reference aurora for the blue box. They are in different locations with (evidently) different drivers. I would suggest to remove this, but I could understand if the authors wish to keep it. If it stays, then please list the caveats, and avoid calling it a "spectrum of the continuum enhancement" as in the caption, or "an estimate of the continuum enhancement above and beyond the coincident aurora."

It looks by eye that the "continuum emission" (blue box) spectrum has a stronger green-line, red-line, and first negative emissions, suggesting more flux, which calls into question the idea that it can be used as a reference using a simple subtraction. Ideally one would want to compare two pixels that have nearly the same "traditional" auroral features. Is this possible, or is there no such pair in this dataset? Please consider this and comment.

Fig 4: Please only plot the Sutoh spectra (diamonds) in regions corresponding to one of the Sternberg windows, or point out that the plotted locations might be contaminated by non-continuum contributions. It appears they were plotted every 50 nm. Most of these are already close to the Sternberg windows, but 650nm is potentially contaminated by N2 1P.

L161: Note that it was scaled from Sutoh to match the data.

L170: The point about the enhanced higher vibrational levels is very interesting. However, the reader needs to be reminded that it is based off of a single comparison, between two pixels that are experiencing very different drivers. It has not been shown conclusively that extra line/band emissions are needed (i.e., maybe if the comparison were more apples to apples, as mentioned above, only continuum would be needed), nor was it shown conclusively that the enhanced bands are correlated with the continuum emission. Please add some "caveat" statement. I would suggest something like: "Future observational work will characterize auroral spectra with and without continuum emission to verify or refute this hypothesis."

L172: It is not really a "survey." One event was studied, and 4 others were briefly shown in Fig 1.

L181: "a new branch type of optical emissions." Please be more specific. The auroral NO₂ continuum has only been measured rarely, but it has indeed been measured and modeled in several previous papers, so it is not brand new. But these observations certainly show its dynamic, meso-scale morphology, and contextualize it with auroral structure.

L182: I do not believe the statement of "unprecedentedly large database... achieved from this study" is accurate. This study

only shows 5 events and only shows spectrograph data for one.

OPTIONAL SUGGESTIONS / TYPOS

L33: airglows --> airglow

I would suggest adding a more concrete "what did we learn" statement in the abstract or conclusion. For example, you could say that the spectral shape of the enhancement appears to fit well with the predicted NO₂ continuum.

L54: auroral --> aurora

L56: What bias are you specifically referring to?

If the journal permits, I would suggest including a video of the RGB image for this event as supplemental information.

L115: "methodology for conclusive detection of continuum emission with the spectrograph" The flow is not clear here. Is this to imply Figure 2 is not conclusive? What about it is not conclusive or needs further depiction?

Fig 3: In the gray "background" region, is the intensity (50-70 R) actually the background emission, or is this some uncorrected background/bias? Is the emission this bright on quiet nights in regions far from the aurora? Or is this possibly due to some weak aurorally-generated continuum just poleward of the bright aurora? Some statements here would help interpretation and future quantitative work.

L131: "4" should be superscript.

L154: "comparable to those reported in conjunction with active auroras and with STEVE" Can you be more specific quantitatively? Are the radiances within 10%? Factor of 10?

L158: "most dubbed" --> "most generally accepted"

L158-9: Does this sentence refer to the (quiet-time, non-auroral) airglow continuum, the auroral continuum, or the STEVE continuum? There are likely various levels of "acceptance" for the NO₂ emission for these three phenomena, so it's best to be specific.

L161: The scaling you used for the Sutoh spectrum should provide you with the column-integrated [NO][O] product, assuming the emission is due to the NO₂ afterglow. I think it would strengthen the impact of this work if this number was reported. It will be a useful target for modeling.

Reviewer #3

(Remarks to the Author)

Please refer to comments in attached PDF file.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have carefully taken into account comments and suggestions in the revised version of the manuscript. I recommend the manuscript to be published.

Reviewer #2

(Remarks to the Author)

I think the updated manuscript is now ready for publication. I only have a couple optional comments that I would like the authors to think about, but I do not need to see a response.

Regarding the [NO][O] product, I thank the authors for considering my comment. However, given the unknown altitude distribution, I think it is difficult/uncertain to constrain [NO][O] itself, but easier to constrain the LoS integral of [NO][O] (units of length⁻⁵ not length⁻⁶). You don't want to give a potentially misleading target for future observational/modeling studies.

Also, the authors may wish to double check whether the emission is truly consistent with Sharp as stated. Sharp showed data observed from a sounding rocket of order 1 R/A, whereas the submitted paper is showing upward viewing data of approximately couple-to-several R/A, if I'm reading it right. Whether this is consistent is difficult to determine given the observation geometries, horizontal structuring of the emission, and unknown altitude distribution. I think it is quite possible

that the authors are presenting something brighter than Sharp reported.

Reviewer #3

(Remarks to the Author)

Review of NCOMMS-24-23303A: Spanswick et al., Through a new lens: structured auroral and neutral atmosphere coupling

Recommendation: Accept after addressing the following minor revisions. The authors have satisfactorily modified the manuscript and provided responses to my comments.

Comments:

Location of figures: This was an issue in the first draft as well. The reviewer has to scroll down multiple pages to look at a figure the authors are discussing early on in the draft.

Throughout the manuscript: There is no space between numerical quantities and their units (e.g., 800nm on line 95). Please add space (e.g., 800 nm) as I believe this improves the formatting.

Line 154: This is a continuation of a comment I made on the previous version of the draft. According to “In comparison, the STEVE continuum emission is known not to relate to appreciable auroral precipitation (Gallardo-Lacourt et al., 2018), evidenced by its much weaker (e.g., Gillies et al., 2019) 557.7 nm intensity than that in our observed continuum structures” mentioned in the revision, it seems that the authors conclude presence of precipitation in their studied events (and essentially absence of precipitation from STEVE) based on the relative intensity of the green line in the 2 events. That is fine. My issue however is with “indicating the presence of auroral precipitation coincident with the continuum emission” in the sentence “Key auroral features, such as the atomic oxygen 557.7 nm and the N2 first positive group, appear to be present within the region of gray-toned emission, indicating the presence of auroral precipitation coincident with the continuum emission”. I originally pointed out atomic oxygen 557.7 nm and the N2 first positive group being present in STEVE even though there’s absence of auroral precipitation so why would the authors conclude/say presence of auroral precipitation just based on detection of atomic oxygen 557.7 nm and the N2 first positive group. As the author mention, maybe the fact that 557.7 nm green line emission levels are much higher in the current study of the continuum can be an indicator of auroral precipitation. Otherwise, simple presence of atomic oxygen 557.7 nm and the N2 first positive emissions doesn’t imply auroral precipitation by itself. I hope the rephrasing of my original comment elucidates the point I was trying to make.

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Review of NCOMMS-24-23303-T: Spanswick et al., Through a new lens: structured auroral and neutral atmosphere coupling

Recommendation: Minor revisions. The authors report in amazing detail on very interesting observations of continuum emissions similar to STEVE phenomena occurring in proximity and conjunction with the aurora. To the best of my knowledge, this is in fact the main factor that separates these observations from previous reports of continuum emission.

Comments:

Page 1, lines 15-20, ending at "...STEVE": The summary section (of this manuscript) includes material that most probably has been already covered in the literature. The authors may consider omitting this part.

Page 1, line 21: Please change "...recognized, however" to "...recognized. However," for better readability

Page 2, line 27: "We present a fresh perspective on this sophisticated coupling". This seems to be a general sentence. The reader may benefit from further elaboration of what the fresh perspective represents scientifically. Omitting the initial part of the summary as suggested above may help with making space for such an expansion/elaboration.

Page 5, line 97: "The top panel (A) presents a one-hour keogram, which is a north-south slice of the RGB image along its central axis, stacked in time, captured at Rabbit Lake". My understanding is that RGB images are all-sky while the keogram seems to be focused on a limited range of latitudes. As such, can the authors clarify what they mean by a north-south slice of an (all-sky?) RGB image (since it suggests that the keogram spans a 180 degree angle)? Also, my guess is that "central axis" refers to the all-sky camera (as opposed to the RGB image). Is that correct?

Page 6, line 131: "emission4"?

Page 6, line 135: "Here, the spatial structuring is distinctly different from STEVE, in that there appears to be no preferential alignment in longitude or latitude, only a clear association with adjacent auroral activity". This is very nicely expressed and demonstrated.

Figure 4, caption: "...and red (region of bright aurora)". I suggest changing the multiple instances of "red" to orange considering red is not used in the labeling of the figure.

Page 7, line 142: "Key auroral features appear to be present within the region of gray-toned emission, including the auroral OI 558 nm and 630 nm as well as the N2 first positive group. This suggests that, unlike observations of other continuum emission structures such as STEVE, there is evidence of auroral precipitation coincident with the observed continuum emission". I had a hard time concluding the authors' interpretation here since as established in figure 1 of Gillies et al., <https://doi.org/10.1029/2019GL083272> STEVE

also includes enhancement of the key auroral features mentioned above. However, it seems difficult to conclude STEVE stems from precipitation mainly based on the latitudes it is observed at. I believe the bottom line here is that “key auroral” features are observed in other luminous events. However, that alone will not be enough to conclude either existence or absence of precipitation as a driving force. Please rephrase.

Page 8, line 160: “In Figure 4, we overplot the expected spectral profile of such NO₂ continuum emission based on the measurements in Sutoh et al.”. The comparison with Sutoh et al. seems to be only at a few points (shown with green diamonds in Figure 4). If the continuum in Sutoh et al. is available in the larger part of the wavelength range, I urge the authors to make the comparison in that entire range as opposed to a few discrete points. Otherwise, any conclusion seems to be close to speculation. This unfortunately seems to be the theme until line 170 on this page.

Page 17, above line 279: “...is overplotted as orange diamonds”. Green diamonds perhaps?

Response to Reviewers

We thank the referees for their thoughtful and constructive comments. We have prepared the below point-by-point responses. Referee comments are included here, in full, with responses included below each specific comment.

Point by Point Response

Reviewer #1 (Remarks to the Author):

The manuscript describes a previously known type of night sky emission in a previously unknown context. Analysis of this new conditions of what the authors call continuum emission in dynamic auroral display demonstrates coupling between the ionospheric plasma and neutral thermosphere processes. These observations are interesting to wider science community. However, the current version of the manuscript would benefit from some clarifications.

- The title could be more specific and more descriptive. Particularly the lens analogy can be misleading as the study uses sky cameras on the ground, which could literally incorporate new lens as new technology.

RESPONSE: We are grateful for the advice, and indeed considered it carefully. It is somewhat difficult to give a "specific and descriptive" title to a newly discovered phenomenon whose underlying mechanisms remain to be explored. As for the lens analogy, "through a new lens" is a common phrase in English, so we do not expect it to cause confusion to the majority of readers, for example, the other two referees have no problem with the title. We therefore respectfully request that the original title be retained. However, we agree with the referee's other comment about the lens analogy in the text (see below) and have revised the wording there.

- The last paragraph of the manuscript refers to a large database from this study. However, 5 events are shown or mentioned in the manuscript, and the characteristics are given to their strongest event, which may or may not be representative. If many more events have been analyzed, that should be stated clearly, and the event description should include statements of common and different properties.

RESPONSE: We thank the reviewer for noting our oversight in describing overall characteristics and properties of the database of events. The two events detailed in

the paper were selected for the visible separation between the continuum structure and the bright aurora (making it easier to see in the imagery). Their spectral properties are in-line with the other events in the database. We have fully analyzed all events as shown in Figure 1 and we have further added a supplementary figure (Figure S1, supplementary material), and have discussed the overall properties observed in a few places of the manuscript where applicable (lines 100-103,141-143, 167-168)

We have further released this list of events to support reproducibility and accessibility of the study. The list of events can be found in supplementary data.

Minor notes:

- line 30: consider omitting “from certain sources” . It does not add information.

RESPONSE: removed.

- line 32: “another” instead of “one other” ?

RESPONSE: changed.

- line 53: “new lens” here makes the reader wonder if this is meant to be literally or figuratively..

RESPONSE: We agree. The phrase has been changed to “.....that affords a new measure of continuum emission observations”

- line 54: “narrow-band filtered cameras” should be rephrased to say that the cameras have narrow-band filters rather than that the cameras are somehow filtered.

RESPONSE: Changed to “cameras utilizing narrow-band optical filters”

- line 64, 65, 67, 82: It is unclear what is meant by “co-averaged frames” , “color stability” and “color profiles”. These terms are worth describing if there are no more descriptive ways of saying the same thing.

RESPONSE: Changed sentence to clarify.... “The nominal imaging mode for TReX- RGB is to average nine 3Hz frames together to provide a 3s cadence data product, in true color.”

Additionally, changed sentence about stability and profiles to clarify, “The operational stability (across temperature, time, within the FoV, etc.) and multiple sensor repeatability of color response of the commercial CMOS cameras...”

- line 75: “explores” rather than “explore”

RESPONSE: Changed.

- line 77: “images” rather than “imagers”

RESPONSE: Changed.

- line 81: If the audience is meant to be larger science community, things like “local light sources” should be explained too.

RESPONSE: Added “(e.g., car headlights)”

- line 90: Is the directional resolution an average of the whole view or precise in all/some directions? Can spectral resolution be given as well?

RESPONSE: Have added spectral resolution and clarified spatial resolution. “Each spectrograph takes 15s images (with 13s integration), producing a complete spectrum from ~400 to 800nm (0.4nm resolution), for each look direction (1 degree resolution along the N-S scan, with an approximate width of ~3 degrees)².”

- line 113: Please provide a number or an order of magnitude for “shortly after”.

RESPONSE: It is almost exactly one minute. This is added in the text.

- line 131: Is “4” meant to be a citation?

RESPONSE: It is. Apologies. Changed to superscript.

- line 143: The notation “OI” could be explained to help a wider audience to follow. Or alternatively consider not using that notation.

RESPONSE: Replaced OI with “atomic oxygen”

- line175: What exactly is meant by “active auroras”?

RESPONSE: Deleted reference to active aurora in the original submitted version line 175, and added clarification to the term in line 197 (of the clean revised version) stating “active auroras (high contrast structures varying on timescale of minutes or less)”.

- Chemical notation often lack the superscripts and subscripts which would make the text much more readable

RESPONSE: Appropriate superscripts and subscripts added

- Emission line wavelengths could be typed in with the same number of digits throughout the manuscript

RESPONSE: Have updated all precise listing of wavelengths to the same number of digits. Have left approximate wavelengths as whole numbers.

Reviewer #2 (Remarks to the Author):

The manuscript presents novel, groundbreaking observations of continuum emission in the aurora. Spectrograph observations of continuum emission in the aurora are rare, and concurrent imagery of 2-D auroral structure are unprecedented. This opens new windows of research into thermosphere-ionosphere coupling in the aurora, especially at mesoscales, and it may have important implications for other research areas like the continuum emission in STEVE.

The data and figures are presented clearly, the methodology is nearly flawless, and the conclusions are sound. I have no major comments, only some minor comments that I believe need to be addressed. But otherwise I suggest this be published promptly.

I have also included some optional suggestions, which the authors should feel free to ignore without comment.

Congratulations to the authors on a wonderful finding, a testament to the capability of the recently deployed TREx network.

MINOR COMMENTS

L32: "from the outer space": Be more specific.

RESPONSE: Changed to “the magnetosphere”

L48: "consistent with"... in what way? In terms of intensity, spectral shape, timing, or what parameter(s)?

RESPONSE: Have modified that sentence to read. “Our observations are consistent with the unexplained emissions noted by Gattinger and Jones⁶ in terms of association with aurora and reported luminosity of continuum emissions (10’s of R/nm). Here, we add critical information about spatial structure, characteristic spectra, and location within auroral dynamics.”

Fig 2: Add information on the assumed emission height for the lat/lon labels.

RESPONSE: Information has been added to the figure captions.

Because the quantitative radiance is important, some more details are needed on calibration. For example, what is the accuracy or systematic uncertainty? Please add this or point to a paper that discusses it in detail.

RESPONSE: We have added a sentence (line 93) to address the radiometric calibration and reference the appropriate paper that discussed the calibration procedure for these specific instruments (please see Section 2 of that paper). New sentence - "Each TREx spectrograph is fully calibrated² to provide quantitative luminosity measurements of the spectral composition."

L108: "Not visible to RGB imager": This gives the impression the RGB and imager disagree on the presence of aurora, but I don't think that's what you mean to imply. Perhaps: "Not visually apparent in the image when compared with the adjacent bright aurora", or "Not visually apparent without contrast adjustment"

RESPONSE: Changed according to the referee's suggestion.

Fig 3: For reproducibility, include the exact timestamps of the image. It says 11:17, but it's not clear if this is 1 image, or an average over the minute, etc. This is important information for readers to interpret the temporal alignment of the two datasets. Include this information both for the RGB camera and the spectrograph.

RESPONSE: Timestamp added.

Fig 4 caption: The colors appear to be listed wrong. I think (red) should be (orange) and (black) should be (blue)? Please check. Also "orange diamonds" should be "green diamonds."

RESPONSE: Apologies, indeed colours were listed wrong. Fixed.

Fig 4: It's troublesome to treat the orange box as the reference aurora for the blue box. They are in different locations with (evidently) different drivers. I would suggest to remove this, but I could understand if the authors wish to keep it. If it stays, then please list the caveats, and avoid calling it a "spectrum of the continuum enhancement" as in the caption, or "an estimate of the continuum enhancement above and beyond the coincident aurora."

It looks by eye that the "continuum emission" (blue box) spectrum has a stronger green-line, red-line, and first negative emissions, suggesting more flux, which calls into question the idea that it

can be used as a reference using a simple subtraction. Ideally one would want to compare two pixels that have nearly the same "traditional" auroral features. Is this possible, or is there no such pair in this dataset? Please consider this and comment.

RESPONSE: Due to the strong auroral signal adjacent to the identified continuum location, we attempt to choose a region for auroral spectral comparison that is both similar in auroral luminosity to the adjacent region and also far enough away from the continuum that we assume no convolution of continuum and aurora is present. In response to the referee's suggestion, we tried to look for pairs of pixels that have comparable green line intensities in our events. See the following example. The auroral pixel is a bit further away from the continuum pixel than in Figure 4, and they are also likely to have different drivers, so the uncertainty pointed out by the referee still exists. However, it can be seen that the residual spectrum is remarkably similar to that in Figure 4. Overall, we agree with the referee that such a difference spectrum may not be accurately called a "spectrum of the continuum" (reworded as suggested in the revision), but may nevertheless capture the essential and repeatable features of the latter.

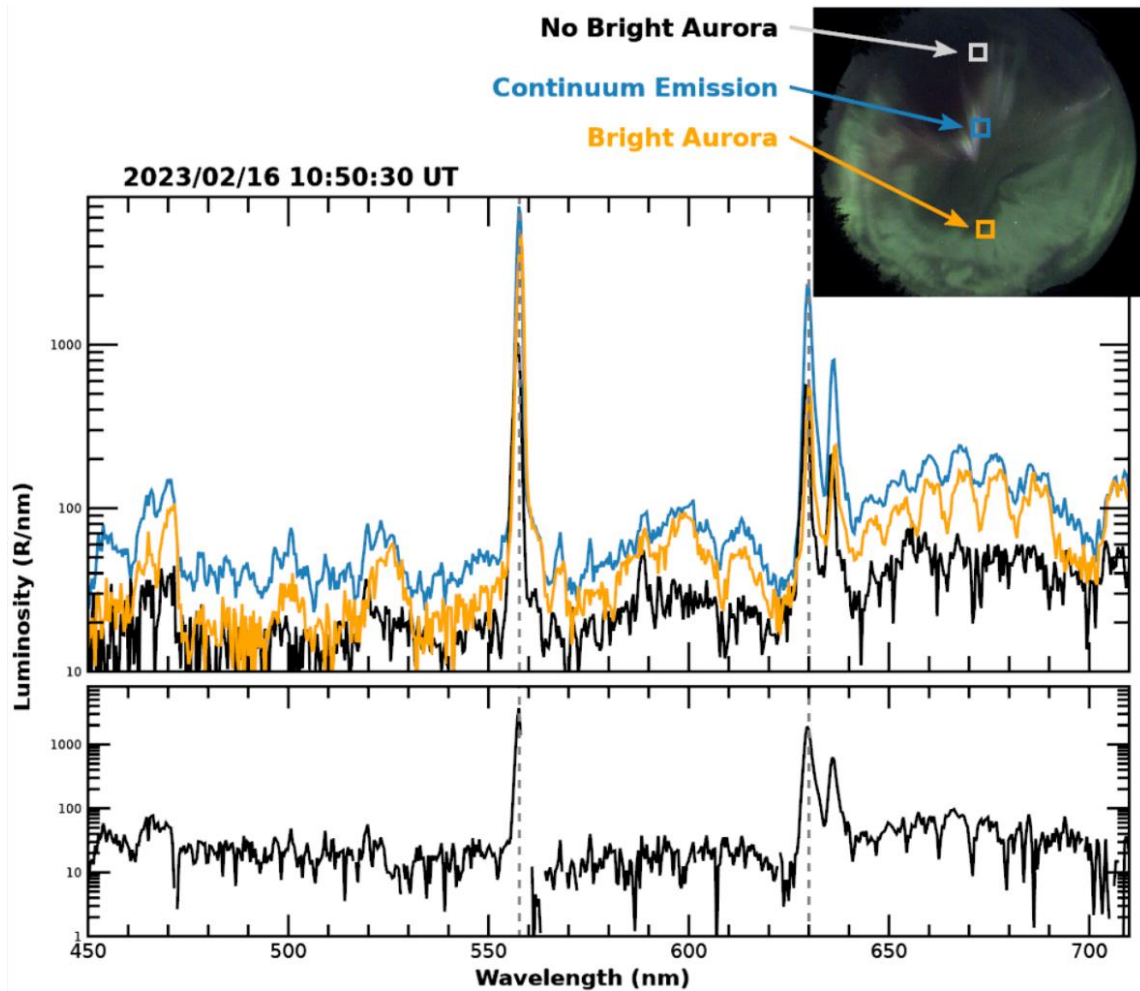


Fig 4: Please only plot the Sutoh spectra (diamonds) in regions corresponding to one of the Sternberg windows, or point out that the plotted locations might be contaminated by non-continuum contributions. It appears they were plotted every 50 nm. Most of these are already close to the Sternberg windows, but 650nm is potentially contaminated by N2 1P.

RESPONSE: Jointly addressed with the comment below.

L161: Note that it was scaled from Sutoh to match the data.

RESPONSE: The NO₂ rate coefficient measurements in Sutoh et al. were only available at several discrete wavelength points. One of these is conveniently located at 502 nm, within the Sternberg window and our selected wavelengths for continuum intensity analysis. In the figure, the NO₂ spectral profile is scaled to match Sutoh et al.'s rate constant and the observed spectral intensity at 502 nm (this note has been added to the text). The result of Sutoh et al. is based on laboratory measurements and is not subject to contamination by N₂ 1P. However, we acknowledge the uncertainty in the above processes. See further arguments and relevant revisions in response to the referee's next comment.

L170: The point about the enhanced higher vibrational levels is very interesting. However, the reader needs to be reminded that it is based off of a single comparison, between two pixels that are experiencing very different drivers. It has not been shown conclusively that extra line/band emissions are needed (i.e., maybe if the comparison were more apples to apples, as mentioned above, only continuum would be needed), nor was it shown conclusively that the enhanced bands are correlated with the continuum emission. Please add some "caveat" statement. I would suggest something like: "Future observational work will characterize auroral spectra with and without continuum emission to verify or refute this hypothesis."

RESPONSE: We agree with the referee. We also note the existence of these high vibrational level N₂ emissions in other continuum events we collected. However, the underlying mechanisms of the continuum and its detailed spectral profile are not yet well understood. The comparison made in this study is based on the hypothesis of a NO₂ continuum spectrum whose rate coefficients are only available at a few sparse wavelength points (Sutoh et al.). We are not in a position to judge where such enhanced N₂ emission bands are an intrinsic part of the continuum itself or caused by other related but separate processes. We have added such a caveat in the revised manuscript (lines 189-192).

L172: It is not really a "survey." One event was studied, and 4 others were briefly shown in Fig 1.

RESPONSE: Addressed jointly with the comment below.

L182: I do not believe the statement of "unprecedentedly large database... achieved from this study" is accurate. This study only shows 5 events and only shows spectrograph data for one.

RESPONSE: We have removed the word unprecedentedly and provided a list of these events in the supplementary information. We have also expanded Figure 1 to include more examples and cited the number of events (32) and overall characteristics in the text (lines 100-103, 141-143, 167-168).

L181: "a new branch type of optical emissions." Please be more specific. The auroral NO₂ continuum has only been measured rarely, but it has indeed been measured and modeled in several previous papers, so it is not brand new. But these observations certainly show its dynamic, meso-scale morphology, and contextualize it with auroral structure.

RESPONSE: We emphasize that we are proposing the NO₂ continuum as a possible candidate for the observed continuum emissions instead of a definitive answer. We have revised the relevant sentence to read: ".....A NO₂ continuum is considered as one possible candidate for the observed continuum. The dynamic variation, the mesoscale morphology, and the contextualization with auroral structures distinguish our observed continuum emission structures from the previously studied ambient NO₂ continuum or STEVE."

OPTIONAL SUGGESTIONS / TYPOS

L33: airglows --> airglow

RESPONSE: changed

I would suggest adding a more concrete "what did we learn" statement in the abstract or conclusion. For example, you could say that the spectral shape of the enhancement appears to fit well with the predicted NO₂ continuum.

RESPONSE: We thank the reviewer for the comment (which is similar to a comment made by another referee) and have modified the last sentence of the summary to read, "We suggest that the meso-scale auroral precipitation may, under certain circumstances, effectively couple to atmospheric chemistry and conditions to produce the continuum structure."

L54: auroral --> aurora

RESPONSE: changed

L56: What bias are you specifically referring to?

RESPONSE: Have changed the wording of that sentence to read, “The advantage of this approach is that it produces continuous datasets of calibrated luminosity within a specific passband, at the cost of systematically ignoring other auroral bands (an observational bias).”

If the journal permits, I would suggest including a video of the RGB image for this event as supplemental information.

RESPONSE: Movie has been generated and included in supplementary material

L115: "methodology for conclusive detection of continuum emission with the spectrograph" The flow is not clear here. Is this to imply Figure 2 is not conclusive? What about it is not conclusive or needs further depiction?

RESPONSE: We agree that our previous wording may be a bit confusing. The comparison of spectra shown in Figure 2 is based on one single elevation bin at different times, while the purpose of Figure 3 is to examine the systematic presence of the continuum emission structure over the field-of-view. We have modified the relevant sentence as “*To examine the systematic presence of the continuum emission structure, we adopt the following methodology to detect the continuum emission with spectrograph measurements.*”

Fig 3: In the gray "background" region, is the intensity (50-70 R) actually the background emission, or is this some uncorrected background/bias? Is the emission this bright on quiet nights in regions far from the aurora? Or is this possibly due to some weak aurorally-generated continuum just poleward of the bright aurora? Some statements here would help interpretation and future quantitative work.

RESPONSE: We may not entirely exclude the presence of remnant dark currents in the background level. However, the $\sim 10\text{-}15$ R/nm spectral intensity over 502-507 nm seems to be in good agreement with previous photographic observations of quiet nightsky (see Figure 1 of Sternberg and Ingham, 1972), leading us to believe that it should mainly represent a combination of the ambient continuum, zodiacal light, and starlight. We have added the statement in the revised manuscript (lines 134-136).

L131: "4" should be superscript.

RESPONSE: Changed.

L154: "comparable to those reported in conjunction with active auroras and with STEVE" Can you be more specific quantitatively? Are the radiances within 10%? Factor of 10?

RESPONSE: There is non-trivial variability of the continuum intensities in our collected events as well as in reported STEVE events. But in general, the difference is found to be within a factor of ~ 5 . We have added this note in the text.

L158: "most dubbed" --> "most generally accepted"

RESPONSE: Changed. See also reply to next comment

L158-9: Does this sentence refer to the (quiet-time, non-auroral) airglow continuum, the auroral continuum, or the STEVE continuum? There are likely various levels of "acceptance" for the NO₂ emission for these three phenomena, so it's best to be specific.

RESPONSE: We fully, agree. We have made the statement specific to quiet time non-auroral continuum, which is the truly "generally accepted" one. We have a hunch that NO₂ emission might be a more plausible mechanism for the auroral continuum than for STEVE, due to the coexistence of strong auroral precipitation and lower emission altitudes of the former, but such a hunch is subject to quantitative examination in future research.

L161: The scaling you used for the Sutoh spectrum should provide you with the column-integrated [NO][O] product, assuming the emission is due to the NO₂ afterglow. I think it would strengthen the impact of this work if this number was reported. It will be a useful target for modeling.

RESPONSE: Yes. The [NO][O] product implied by the scaling here is estimated to be $\sim 4 \times 10^{20} \text{ cm}^{-6}$, following the model in Harding et al. (2020). The value is similar to the evaluations in Sharp [1975]. This has been added to the text.

Reviewer #3 (From PDF file):

Review of NCOMMS-24-23303-T: Spanswick et al., Through a new lens: structured auroral and neutral atmosphere coupling

Recommendation: Minor revisions. The authors report in amazing detail on very interesting observations of continuum emissions similar to STEVE phenomena occurring in proximity and conjunction with the aurora. To the best of my knowledge, this is in fact the main factor that separates these observations from previous reports of continuum emission.

Comments:

Page 1, lines 15-20, ending at "...STEVE": The summary section (of this manuscript) includes material that most probably has been already covered in the literature. The authors may consider omitting this part.

RESPONSE: Respectfully request to keep this text (as advised by editor) to support placing the current results in context of the significant STEVE advancements.

Page 1, line 21: Please change "...recognized, however" to "...recognized. However," for better readability

RESPONSE: Changed.

Page 2, line 27: "We present a fresh perspective on this sophisticated coupling". This seems to be a general sentence. The reader may benefit from further elaboration of what the fresh perspective represents scientifically. Omitting the initial part of the summary as suggested above may help with making space for such an expansion/elaboration.

RESPONSE: Rephrased to "*We suggest that the meso-scale auroral precipitation may, under certain circumstances, effectively couple to atmospheric chemistry and conditions to produce the continuum structure.*"

Page 5, line 97: "The top panel (A) presents a one-hour keogram, which is a north-south slice of the RGB image along its central axis, stacked in time, captured at Rabbit Lake". My understanding is that RGB images are all-sky while the keogram seems to be focused

on a limited range of latitudes. As such, can the authors clarify what they mean by a north-south slice of an (all-sky?) RGB image (since it suggests that the keogram spans a 180 degree angle)? Also, my guess is that “central axis” refers to the all-sky camera (as opposed to the RGB image). Is that correct?

RESPONSE: The referee is correct. The cameras are installed such that the vertical axis of the detector (detector-y) is aligned with geomagnetic north. A keogram is generated via the meridian line of pixels that pass through the center of the image (i.e., directly overhead at the station) in the N-S direction. We generate the latitude axis by using the mapped (110km) geographic coordinates along this central axis. In general, the camera FoV will allow for use of pixels down to ~5 degrees elevation angle before obstructions such as trees become an issue.

Page 6, line 131: “emission4”?

RESPONSE: Corrected citation format.

Page 6, line 135: “Here, the spatial structuring is distinctly different from STEVE, in that there appears to be no preferential alignment in longitude or latitude, only a clear association with adjacent auroral activity”. This is very nicely expressed and demonstrated.

RESPONSE: We thank the referee for the comment.

Figure 4, caption: “...and red (region of bright aurora)”. I suggest changing the multiple instances of “red” to orange considering red is not used in the labeling of the figure.

RESPONSE: Changed.

Page 7, line 142: “Key auroral features appear to be present within the region of gray-toned emission, including the auroral OI 558 nm and 630 nm as well as the N2 first positive group. This suggests that, unlike observations of other continuum emission structures such as STEVE, there is evidence of auroral precipitation coincident with the observed continuum emission”. I had a hard time concluding the authors’ interpretation here since as established in figure 1 of Gillies et al., <https://doi.org/10.1029/2019GL083272> STEVE also includes enhancement of the key auroral features mentioned above. However, it seems difficult to conclude STEVE stems from precipitation mainly based on the latitudes it is observed at. I believe the bottom line here is that “key auroral” features are observed in other luminous events. However, that alone will not be enough to conclude either

existence or absence of precipitation as a driving force. Please rephrase.

RESPONSE: We recognize the potential confusion with respect to our observations and previous results for the STEVE continuum emission. It has been shown that STEVE does contain a nontrivial 630 nm emission component that mostly stems from thermal excitation under highly elevated electron temperature, similar to SAR. There is a weak (compared to the background airglow and excluding continuum enhancement) 557.7 nm component in STEVE, which may be contributed by thermal excitation, possible low-energy electron acceleration in the local ionosphere (Gasque et al., GRL 2023), and perhaps some very weak auroral precipitation. Although auroral precipitation may not be zero in STEVE (e.g., Liang JGR 2021), it is certainly much weaker than in our auroral continuum events, as can be inferred via a comparison between the 557.7 nm spectral intensity in Gillies et al. (2019) to that in our events (see Figure S1 in supplementary material). It is reasonable to conclude that auroral energy deposition likely plays a more pivotal role in our observed continuum emissions than in STEVE. We have rephrased the relevant sentences (lines 154-159) according to the above arguments.

Page 8, line 160: “In Figure 4, we overplot the expected spectral profile of such NO₂ continuum emission based on the measurements in Sutoh et al.”. The comparison with Sutoh et al. seems to be only at a few points (shown with green diamonds in Figure 4). If the continuum in Sutoh et al. is available in the larger part of the wavelength range, I urge the authors to make the comparison in that entire range as opposed to a few discrete points. Otherwise, any conclusion seems to be close to speculation. This unfortunately seems to be the theme until line 170 on this page.

RESPONSE: Unfortunately, the NO₂ rate coefficient measurements in Sutoh et al. (and other similar studies) were only available at several discrete wavelength points. However, it is theoretically expected that the NO₂ continuum itself does not embed individual N₂ or O emission lines. All these existing NO₂ rate studies (see e.g., Fontijn et al, 1964; Vanpee et al., 1971; Sutoh et al., 1980) have assumed a smooth interpolation between measured wavelengths to derive the spectral profile. We emphasize that the phenomenon reported in this paper is novel, and the current understanding of the underlying mechanisms of continuum emissions and their characteristic spectra remains limited. Therefore, some speculation is unavoidable at this stage, but may serve as a useful initial guess to guide future modeling efforts, as pointed out by another reviewer. That said, we have modified the relevant sentences (now lines 175-192), acknowledging the limitations of both the measurements and our deductions.

Page 17, above line 279: "...is overplotted as orange diamonds". Green diamonds perhaps?

RESPONSE: Changed.

Additional References

Gasque, L. C., Janalizadeh, R., Harding, B. J., Yonker, J. D., & Gillies, D. M. (2023). It's not easy being green: Kinetic modeling of the emission spectrum observed in STEVE's picket fence. *Geophysical Research Letters*, 50, e2023GL106073. <https://doi.org/10.1029/2023GL106073>

Liang, J., St-Maurice, J. P., & Donovan, E. (2021). A time-dependent two-dimensional model simulation of lower ionospheric variations under intense SAID. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029756. <https://doi.org/10.1029/2021JA029756>

Fontijn, A., Meyer, C. and Schiff, H. (1964), Absolute Quantum Yield Measurements of the NO–O Reaction and Its Use as a Standard for Chemiluminescent Reactions. *The Journal of Chemical Physics*, 40, 64. <http://dx.doi.org/10.1063/1.1724895>

Vanpee, M., K. D. Hill and W. R. Kineyko (1971), Absolute rate constant measurements for the radiative combination of atomic oxygen with nitric oxide, *AIAA. J.*, 9, 135.

Response to Reviewers

Once again, we thank the referees for their thoughtful and constructive comments. We have prepared the below point-by-point responses. Referee comments are included here, in full, with responses included below each specific comment.

Point by Point Response

Reviewer #1 (Remarks to the Author):

The authors have carefully taken into account comments and suggestions in the revised version of the manuscript. I recommend the manuscript to be published.

Reviewer #2 (Remarks to the Author):

I think the updated manuscript is now ready for publication. I only have a couple optional comments that I would like the authors to think about, but I do not need to see a response.

Regarding the [NO][O] product, I thank the authors for considering my comment. However, given the unknown altitude distribution, I think it is difficult/uncertain to constrain [NO][O] itself, but easier to constrain the LoS integral of [NO][O] (units of length^{-5} not length^{-6}). You don't want to give a potentially misleading target for future observational/modeling studies.

RESPONSE: In our previous evaluation we have assumed a scale height of 50 km, the same as in Harding et al. (2020). We agree with the referee that such value is subject to uncertainty due to unknown altitude profiles. In the revised manuscript we have followed the referee's suggestion and present the column [NO][O] density product instead ($\sim \times 10^{27} \text{ cm}^{-5}$).

Also, the authors may wish to double check whether the emission is truly consistent with Sharp as stated. Sharp showed data observed from a sounding rocket of order 1 R/A, whereas the submitted paper is showing upward viewing data of approximately couple-to-several R/A, if I'm reading it right. Whether this is consistent is difficult to determine given the observation geometries, horizontal structuring of the emission, and unknown altitude distribution. I think it is quite possible that the authors are presenting something brighter than Sharp reported.

RESPONSE: Sharp (1978) presented four events. Inferred from his Figure 1 and 2, the peak intensities of the continuum emissions at 520 nm are between $\sim 1\text{-}3 \text{ R/A}$ ($10\text{-}30 \text{ R/nm}$), which is

indeed compatible with what we inferred in a majority of continuum structure events we collected (see Figure S1)

Reviewer #3 (Remarks to the Author):

Review of NCOMMS-24-23303A: Spanswick et al., Through a new lens: structured auroral and neutral atmosphere coupling

Recommendation: Accept after addressing the following minor revisions. The authors have satisfactorily modified the manuscript and provided responses to my comments.

Comments:

Location of figures: This was an issue in the first draft as well. The reviewer has to scroll down multiple pages to look at a figure the authors are discussing early on in the draft.

Throughout the manuscript: There is no space between numerical quantities and their units (e.g., 800nm on line 95). Please add space (e.g., 800 nm) as I believe this improves the formatting.

RESPONSE: Format corrected as suggested by the referee.

Line 154: This is a continuation of a comment I made on the previous version of the draft. According to “In comparison, the STEVE continuum emission is known not to relate to appreciable auroral precipitation (Gallardo-Lacourt et al., 2018), evidenced by its much weaker (e.g., Gillies et al., 2019) 557.7 nm intensity than that in our observed continuum structures” mentioned in the revision, it seems that the authors conclude presence of precipitation in their studied events (and essentially absence of precipitation from STEVE) based on the relative intensity of the green line in the 2 events. That is fine. My issue however is with “indicating the presence of auroral precipitation coincident with the continuum emission” in the sentence “Key auroral features, such as the atomic oxygen 557.7 nm and the N2 first positive group, appear to be present within the region of gray-toned emission, indicating the presence of auroral precipitation coincident with the continuum emission”. I originally pointed out atomic oxygen 557.7 nm and the N2 first positive group being present in STEVE even though there’s absence of auroral precipitation so why would the authors conclude/say presence of auroral precipitation just based on detection of atomic oxygen 557.7 nm and the N2 first positive group. As the author mention, maybe the fact that 557.7 nm green line emission levels are much higher in the current study of the continuum can be an indicator of auroral precipitation. Otherwise, simple presence of atomic oxygen 557.7 nm and the N2 first positive emissions doesn’t imply auroral precipitation by itself. I hope the rephrasing of my original comment elucidates the point I was

trying to make.

RESPONSE: The excitation energy of 557.7 nm and N2 1PG are 4.2 eV, and 7.4 eV, respectively. We agree with the referee that they may also be caused by non-aural sources such as thermal excitation or local acceleration in the ionosphere (Mende, 2019GL086145; Gasque et al., 2023GL106073). On the other hand, the N2+ 1NG emission requires 18.8 eV excitation energy and is usually regarded as a more robust signature of auroral precipitation. We do see strong N1+ 1NG enhancement in our continuum structure events (see Figure 4 and Figure S1). In contrast, STEVE is known to feature weak or none N2+ 1NG emissions ((Gillies et al., 2019GL083272; Mende, 2019GL086145). We have modified the relevant sentences in the manuscript as follows

“~~Key Auroral features~~, such as the atomic oxygen 557.7 nm and the N₂⁺ first ~~positive~~negative group (1NG), appear to be present within the region of gray-toned emission. Since the N₂⁺ 1NG requires ~19 eV excitation energy, its presence is usually regarded as a signature of , indicating the presenece of auroral precipitation ~~coincident with the continuum emission~~. In comparison, the STEVE continuum emission is known not to relate to appreciable auroral precipitation (Gallardo-Lacourt et al., 2018), evidenced by its much weaker (e.g., Gillies et al., 2019; Mende et al., 2019) 557.7 nm and N₂⁺ 1NG intensitiesy than that in our observed continuum structures.”