Reply to reviewers' comments

We thank the both reviewers for careful reading and suggestions. Their comments are well justified. The manuscript was revised, following the suggestions. Here are our reply and changes made in the manuscript.

Reviewer 1

Comment The authors used German auroral photos during the May 2024 storm to find a new type of stable auroral red arcs and classified the greenish feature as "stable auroral green arcs. This is an interesting attempt. However, the authors did not show much evidence except for their morphological discussions. The authors' auroral photos and the morphological descriptions rather reminds me of typical midlatitude aurorae with ray structure, in contrast with the typical SAR arc morphology (Kozyra et al., 1997). Moreover, the term of "stable auroral green arcs" was used in Mendillo et al. (2016) that the authors did not cite. Unless the authors show substantial independent evidence, their manuscript does not seem convincing enough to satisfy the threshold of publication in Annales Geophysicae. Of course, I am happy to take a closer look if the authors provide further supporting evidence.

Reply Due to the referee's comments and additional conversations with auroral experts at the University of Michigan and the University of Alaska, we have now revised the title and text in the paper to call this event a red/green "Christmas" auroral event over Germany. We agree not to call this a SAR arc. We have also removed reference to a SAG arc. The entire topic of what is or isn't a SAR arc is quite controversial and we feel that it is best for the article to avoid it.

Major Comments

Comment The SAG (stable auroral green) arcs have been once used in Mendillo et al. (2016) that the authors did not cite. What is the difference of their SAG arcs but Mendillo et al.'s SAG arcs? What is the authors' novelty on SAG arcs against what Mendillo et al. (2016) discussed?

Reply Thank you for the reference to the Mendillo et al paper. We did not see it before. The authors mention the phrase SAG arcs once (and only once), but it is not clear whether they are referring to the same thing as in our paper or not. To remove any confusion of meaning of the term SAG arc, we have removed reference to it throughout the revised paper. The title of our paper is now: "High Temporal- and Spatial-Resolution Photographs of the "Christmas" Red-Green Auroras Taken over Germany During the Main Phase of the May 10-11 2024 SYM-H = -518 nT Superstorm".

Comment Apart from the authors' own articles, their references are extremely old. Their latest external references date only down to 2008, except for the SuperMAG dataset (Gjerloev, 2009, 2012; Newell and Gjerloev, 2011) and the OMNI dataset (King and Papitashvili, 2020). This gives

me a worry whether the authors have seriously surveyed the recent research developments upon writing this manuscript.
Especially for the May 2024 storm, we have more than tens of publications. Apart from their self citations, none has been properly addressed.

Reply The main focus of this paper are the streaks/rays seen in the high time resolution photos taken over Germany. These observations have direct relevance to the mechanisms creating both the red and green auroras. Thus in our writeup we have referenced papers dealing with the mechanisms of red aurora formation. These have tended to be older references as you mentioned. That is because this is a very old topic and basically all possible mechanisms have already been discussed. There has not been any concensus as to what mechanism or mechanisms are the correct ones. Referee #2 has directed us to some possibly relevant red aurora mechanisms which we had missed before and are now added to the revised paper. But these are again old papers (1979, 1976, and 2002). We have now added mention to the Mendillo et al. (2016) paper. However please note that they conclude that energetic electron precipitation is a likely red aurora generation mechanism, a topic which has been mentioned in the earlier references listed in the paper.

Yes, one of us has collected ~150 articles on the May 2024 superstorm. Please note that we have referenced the first published paper on the 2024 superstorm (Hajra et al. 2024), and to our reading, it is the only one that discusses the details of the interplanetary causes of the three main phase steps of the storm. It was already referenced in the original version of the paper. Because of your requests, we now have expanded the discussion with the addition of the references that you mentioned on red auroras, and one more on the interplanetary causes of supersubstorms and the storm recovery phase (Hajra et al. 2025).

Comment The authors claim that Figure 3 represents SAR arcs. However, this shows non reddish coronations and evident vertical structures, in contrast with SAR arcs that appear monochromatic reddish glows without evident structure (Kozyra et al., 1997). The authors explicitly admit such a discrepancy as, "The red portion of the aurora is not a featureless reddish display similar to the aurora shown in Figure 1, but there are rays in the red auroras from the upper right downward slightly to the left". Figure 3 probably shows no new feature for SAR arcs but normal auroral displays. The authors need to show proper independent measurements to interpret Figure 3 as SAR arcs.

Reply Yes. We have now revised the paper both in the title and in the body of the paper removing the claim that the red aurora over Germany were SAR arcs. The red aurora shown in Kozyra et al, (1997) were taken from long distances away and in those days there were no high-speed cameras to see possible streaks.

Comment It is better to examine auroral electron precipitations to figure out whether they are looking at SAR arcs or aurora caused by broadband electron precipitations. The authors are

requested to consult DMSP satellite data to figure out whether they can justify their claim with the observational data. At least, from this picture, what they photograph does not look like a SAR arc.

Reply We have looked at all 4 DMSP satellites and found that none of them were over our German sites at the times of our red aurora observations.

Comment I am not convinced with their comparison of Figures 1 and 3. Figures 1 and 3 are photographed at Los Angles on 12 Apr 1981 and at and Braunschweig at 22:16 UT on 10 May 2024. They are different events. Numerous publications have documented colorful auroral displays that extended to the European sector during the May 2024 storm (e.g., Spogli et al., 2024; Grandin et al., 2024). This is not something terribly new either. The authors need to contextualise their photos and movies to such citizen-science approaches.

Reply Corrected. We have added the above two references in the revised version of the paper as mentioned above. We have removed the old Figure 1 (and Figure 2) and reformatted the presentation. We agree that the Los Angeles auroral figure is not needed.

Minor Comments

Comment Page 1 Line 10 The authors need some references to justify their statement. Who made such an interpretation? Who examined the spectrum? The spectroscope showed up decades after the French Revolution.

Reply Corrected. We now refer to these are red aurora observations. We do not have spectrometer information, but we now mention two papers with spectral results that disagree with each other. We doubt that the observations are wrong, but we think that there are different types of red auroras. One of our conclusions is that for our event, we believe that energetic electron precipitation is the main source of the red aurora. But we also conclude that other red auroral sources may be present at lower levels of intensity. There may be many types of middle latitude red auroras.

Comment Page 1 Line 12 The authors need to clarify from where "SAR arcs were seen ∼20% of the time".

Reply Done.

Comment Figure 1 The authors need to add proper credits for this figure. We can see James Young's name in the photo, while it is important to address that in the figure caption.

Reply Figure 1 has been removed.

Comment Page 2 Line 20 The authors need to show proper references to justify their statement on their statement: " the announcer told viewers to go outside and experience the unusual red aurora". If this is one of the authors' personal recollection, the authors should clarify so.

Reply Done. Removed. It was BTT that made the observation. He was asked to present the LA red aurora photo to the President of Caltech, which he did in an half hour presentation.

Comment Page 4 Line 56 Tsurutani et al. (2003) documented the aurora extending down to L = 1.3, rather than L ≈ 3. It should be better to use their own value.

Reply Corrected. This was not necessary in the paper revision, so it has been removed.

Comment Page 4 Line 62 How did the authors define the auroral duration as ~19:00 and 24:00 UT? I could not find any references to justify this statement. Did they make some survey? Did they rely on some citizen science surveys (e.g., Grandin et al., 2024) for this duration? Or did they indicate this duration from one of the German authors' personal experience?

Reply Corrected. The new Figures 2 to 4 span this time frame. The times of the auroral images are now indicated in Figure 1.

Comment Page 5 Line 76 I am slightly confused here. Why are they comparing Figures 1 and 3? They are from different storms with different magnitude in the most negative Dst suppressions. We learn extremely little from comparison of the red aurora in Los Angeles in Apr 1981 and red and green aurorae in Germany in May 2024.

Reply Corrected. Figure 1 has been removed.

Comment Page 6 Line 93 In contrast with the authors' claim, rays are visible at least in the supposed "SAR arc".

Reply Corrected. This was what we were trying to say and is the main point of the paper. We have made this clearer in the revised version.

References

Grandin et al. (2024) The Gannon Storm: Citizen Science Observations during the Geomagnetic Superstorm of 10 May 2024, Geoscience Communication, 7, 297–316

Kozyra et al. (1997) High-Altitude Energy Source(s) for Stable Auroral Red Arcs, Reviews of Geophysics, 35, 155-190
Mendillo et al. (2016) A Stable Auroral Red (SAR) Arc with Multiple Emission Features, Journal of Geophysical Research: Space Physics, 121, 10564-10577
Spogli et al. (2024) The Effects of the May 2024 Mother's Day Superstorm over the Mediterranean Sector: From Data to Public Communication. Annals of Geophysics, 67, PA218

Reply Thank you. All references have been added.

Reviewer 2

Comment The article appears very interesting and provides a great overview of auroral features observed during the recent large geomagnetic storms over mid-latitudes in Europe. I would encourage the authors to smooth somewhat the statements about "new scientific findings", especially in the abstract. I believe that many of the auroral features described here have been observed before, though not necessarily reported in details. I also would suggest to expand the discussion of possible mechanisms for parallel electric fields, as I wrote in more detailed comments below. I believe the article is suitable for publication after a minor revision.

Reply Thank you for your very helpful comments. From your comments and from other ones from auroral experts that we received after the paper submission, we believe that there is a great deal of confusion on what is a SAR arc and what is not. We have therefore avoided the terms SAR arc and SAG arc (see comments to referee #1 concerning SAG arcs) in the title and the body of the paper.

Comment Line 6-7: The statement about a new scientific finding appears very strong. I assume, the diffuse green aurora below the SAR arcs has been observed before. I would suggest to re-phrase this statement in the abstract.

Reply Done. We looked in both the literature and asked external auroral experts for a proper reference to diffuse green auroras below red auroras and were not able to find one. We contacted people at the University of Michigan and the University of Alaska and asked, without success. However this still does not mean that there is no such reference. We have bypassed the issue to changing the title of the paper and removing the useage of the words SAG arcs and SAR arcs in the observational part of the paper. We now do not claim that this is a new observation of green auroras under red auroras.

Comment Line 31 and Fig. 2 caption: The vertical gray shading at 6 - 6:30 UT is mentioned twice, but I do not see it in the figure, only the vertical dashed red line. Besides, Fig. 2 covers the 4-day interval. I assume the authors mean 6 - 6:30 UT, 13 April.

Reply Corrected. Figures 1 and 2 have been removed from the paper.

Comment Line 57: It is a minor point but the correct plural form of “radius” is “radii” or “radiuses”. In principle, the plural form of “aurora” is “aurorae”, but “auroras” is also acceptable.

Reply Corrected.

Comment Line 63-73 and Fig. 3: Coming back to the “new scientific finding” statement. I remember myself observing very similar auroral features during large geomagnetic storms, also in Germany. But I am not sure if every feature has been reported in details in the literature.

Reply Thank you for the comment. In discussing this with other auroral experts we have been told similar stories. But no one knew of any reportage in the literature (that we could quote). We have asked around but without success. We no longer state whether this observation is new or not. However the streaks covering both the red and green auroras are new. Older cameras would not have the capability of making such high time resolution images. This latter feature is the main point of the paper. It gives us new information on the red aurora generation mechanism for this particular red auroral case that occurred over Braunschweig and Goettingen, Germany.

Comment Line 179-180: I think that another mechanism could be also responsible for parallel electric fields in this context, described by Goertz and Boswell (1979) https://doi.org/10.1029/JA084iA12p07239, due to the effects of finite electron inertia term in dispersive Alfven waves. The mechanism proposed by Hasegawa (1976) is due to the finite ion Larmour radius correction term. In fact, I would expect the Goertz and Boswell term to be more relevant in this context, as it works in the vicinity of auroral acceleration region. The interplay between the two dispersive mechanisms along magnetic field lines is described by, e.g., Pokhotelov et al., (2002) https://doi.org/10.1029/2001JA000134. Perhaps this interplay should be briefly discussed here.

Reply Thank you for the references, which we missed. A discussion of these mechanisms have now been added to the revised version of the paper.

Lisgt of changes

- Title was updated to "High Temporal- and Spatial-Resolution Photographs of the “Christmas” Red-Green Auroras Taken Over Germany During a Main Phase of the 10–11 May 2024 SYM-H = −518 nT Superstorm"
- The author order was updated.
- Author address field (GSL) was updated.

- Abstract was rewritten from scratch.
- Section 1. Paragraph 1 was inserted. Paragraph 4 was inserted.
- Section 2. Section header was changed into "Background Information".
- Section 3. Section header wss changed into "The Magnetic Storm of 10–11 May 2024".
- Figures 1 and 2 in the original manuscript were deleted.
- Figure 1 in the revision shows the solar wind data and geomagnetic indices.
- Section 3. Paragraph 3 (page 5, line 85) was added.
- Section 4. Bullet point 2 was inserted.
- Section 5. Paragraphs 3 and 4 (page 8) were mostly rewritten.
- Section 6 was rewritten.
- References to Goertz and Boswell (1979), Grandin et al. (2024), Kataoka et al. (2024), Kozyra et al. (1997), Mandillo et al. (2016), Pokhotelov et al. (2008), Rassoul et al. (1993), Shiokawa et al. (1997), Spogli et al. (2024) were added.