*AGU Advances*

Authors' Response to Peer Review Comments on

**Are Dawn Storms Jupiter's auroral substorms?**

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## Authors' Response to Peer Review Comments on Original Version of Manuscript (2020AV000275)

*Please see the attachment that begins on the next page.*

We would like to thank the three reviewers for their valuable comments. We have modified the manuscript accordingly. In addition, we also slightly updated the figures in the supplemental material to remove some unnecessary artifacts in some images.

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Reviewer #1 Evaluations:
Recommendation: Return to author for minor revisions
Significant: Yes, the science is at the forefront of the discipline.
Supported: Mostly yes, but some further information and/or data are needed.
Referencing: Yes
Quality: Yes, it is well-written, logically organized, and the figures and tables are appropriate.
Data: Yes
Accurate Key Points: Yes

Reviewer #1 (Formal Review for Authors (shown to authors)):

This paper provides a tremendous new perspective on the evolution of auroral forms at Jupiter from the Juno ultraviolet spectrograph. A detailed description of "dawn storms" is given with ample supporting UVS imagery. The paper is timely and represents a significant advancement in our understanding of the temporal evolution of nightside to dawnside auroral forms (previously the nightside was inaccessible with HST images). However, there are a few details related to the terrestrial comparison that should be improved prior to publication. These suggestions are summarized below.

Major comments:

The paper would be much improved if the terrestial "substorm" terminology was carefully delineated. In the current form, there are several instances where terrestrial terminology is adopted for Jupiter and this may be misleading or even confusing. For example, Lines 386-388 state, "The magnetospheric processes associated with substorm magnetotail reconfigurations....have also been observed at Jupiter". Substorm is a very specific instance of a solar wind-driven magnetotail reconfiguration at Earth. We don't know, exactly, what is happening at Jupiter, but it is unlikely that the external solar wind driver plays an important role. The best practice here is simply to refer to "magnetotail reconfigurations", omitting the word "substorm". Likewise, "storm" is also reserved for the hierarchy of solar wind interactions at Earth. It might be helpful to state "storm-like" vs. "storm".

We have cross-checked all the instances in which the word “storm” and we verified that it is always used in the expression “dawn storm”, which itself has a specific meaning in the Jovian context and has been used as such in the literature for more than two decades. Hence we decided to keep this expression for consistency with earlier works. However, we share the reviewer’s concern that the word “storm” has a lightly different meaning depending on the planet. A discussion among the magnetospheric communities, aiming at standardizing the nomenclature and the definition of the various events across the solar system, would certainly be useful at some point, but is out of the scope of the present paper.

The introduction should be expanded. A definition of the terrestrial substorm (growth, expansion, and recovery) phases should be provided. In addition, the physics of current sheet thinning is likely the common thread for comparing Earth and Jupiter. The physical process(es) leading to current sheet thinning may be completely different, but the auroral consequences are likely to be very similar. An overview of the current sheet thinning processes (e.g., divergent azimuthal flows) would make an nice addition to the introduction and would serve as an obvious segue into defining terrestrial substorm and/or jovian magnetotail reconfiguration processes. The following paper provides a good discussion of current sheet thinning and could be summarized quickly in an introductory paragraph.

Hsieh, M.-S., and Otto, A. (2015), Thin current sheet formation in response to the loading and the depletion of magnetic flux during the substorm growth phase. J. Geophys. Res. Space Physics, 120, 4264- 4278. doi: 10.1002/2014JA020925.

We agree with the reviewer as our introduction was a bit short and lacked an introduction to the substorms. Thus we have expanded the introduction to better introduce the substorms and their relevance to Jupiter. It was however not clear to us that discussing current sheet processes was the best approach to connect dawn storms and substorms because our observations focus on the aurorae and not on the magnetospheric processes. Moreover, to the best of our knowledge, studies of the current sheet at Jupiter focused on its mean characteristics rather than their variations (see Artemyev et al. 2014 for example). As a side note, recent investigations at Saturn have shown that magnetic reconnection can be triggered in the dayside magnetodisc (Guo et al. 2018, Nature Astro.), indicating that different processes for current sheet thinning could take place at giant planets. Instead we decided to build this connection and introduce the definition of substorms at Earth through past studies that explicitly mentioned the term “substorm” in the Jovian context (Ge et al., 2007; Kronberg et al., 2005, 2008; Krupp et al., 1998).

Minor comments:

Line 160: Here (or the first reference to supplemental material), define Figure S1 as belonging to the supplemental material. Without noticing the supplement, Figure S2 could be referring to Figure 2 "south"...as this reviewer was prone to think!

Done.

Line 175: The the

Corrected.

Line 196-197: The times don't match the figure.

We have corrected one of the times that was indeed incorrect and we clarified the selection of the images for Figure 3.

Line 218: Expansion phase is understood to be a poleward expansion of the auroral emission. "Expansion phase" is very "substorm" specific. Suggest (here and elsewhere) replacing with "poleward expansion". If equatorward expansion is also observed, then this point should be made very clear.

We understand the concerns of the reviewer, but on the other hand, it is our opinion that “expansion phase” is just too generic a term to consider it exclusively reserved for terrestrial substorms. A quick search on the internet showed us that this expression is used in many domains of sciences, from physics to economics, or computer sciences. As a reasonable compromise, we made sure that, for every use of the expression “expansion phase” in our text, it was clear that we were discussing the longitudinal and latitudinal expansion of a bright section of the auroral arc in the context of dawn storms. In some cases, we added a few words to clarify our intent.

Line 227-228: For perpendicular propagation in the equatorial plane, do you really mean "fast mode"?

Indeed, this is correct. We have modified the text accordingly and we have added a reference to Kivelson [2015], who discussed that matter.

Line 297: Describe the results from Zhang et al., 2020. How is it different?

In the traditional picture of a planetary magnetosphere, the magnetic field lines near the magnetic pole are extended to the cusp or tail lobe and open to the solar wind. Therefore, the auroral emissions are expected to be very low in the polar cap region. However, UV images of Jupiter's polar aurorae reveal that most of polar cap is often filled with auroral emissions, which is not consistent with filed line connected to the solar wind. In the simulations of Zhang et al. (2020), the magnetic field lines from the near-pole region are helical and extend to the night tail. The magnetopause reconnection is too weak to balance the magnetic flux transport by planetary rotation (i.e., Vasyliunas cycle), so that the majority of polar cap region is filled with closed field lines rather than open field lines. Their results are thus more compatible with the observed auroral morphology. Because dayside magnetopause reconnection is so limited at Jupiter, the simulations of Zhang et al. 2020 describe a magnetosphere which is essentially closed and the few flux tubes connected to the solar wind are entangled an intertwined with closed flux tubes mapping to the distant magnetotail. We have completed the sentence to clarify this point.

Lines 330-331: Describe in specific detail what is meant by "outside-in" vs. "inside-out". This isn't clear. Perhaps it is necessary is clarify in the previous paragraph. What is the specific analogy with Earth? Are you referring to near Earth current sheet thinning (L = 6-10 R_E) while at Jupiter the current sheet thinning occurs at a relatively larger distance? It might depend on how you normalize distances in the magnetotail.

There are two key processes in terrestrial substorm, i.e., the mid-tail magnetic reconnection at ~20 $R_E$ and near-Earth current disruption at ~ 10 $R_E$. However, the causality between the two processes has been debated for decades, and thus two privileged models (i.e., outside-in and inside-out models) were proposed to explain their causality, thus, to unlock the substorm mystery. At Earth, the terminology "outside-in" designates the near-Earth neutral line model, for which the disturbance originates in the tail in the tail as a result of reconnection, which would eventually cause a current disruption closer to the Earth (~10$R_E$) (Baker et al. 1996). The "inside out" model designates the near Earth current disruption model (Lui et al, 2015), for which plasma instabilities disrupt the current sheet around 10 $R_E$, and the perturbation would propagate towards the tail, triggering reconnection of field lines downstream (the above definitions are adapted from Sandhu et al. 2019). We use them here in the same broad sense as at Earth, i.e. in the outside-in scenario, the event starts with reconnection in the distant magnetotail (~90RJ) before propagating inward and disrupt the plasma sheet closer to Jupiter (~60-40RJ, where the main emissions map) and finally trigger plasma injections in the middle magnetosphere (30-10 RJ). On the other hand, in the inside-out scenario, the event would start in the middle magnetosphere with plasma injections, before disrupting the region where the main emissions maps (40-60 RJ) and finally triggering reconnection and the release of plasmoids in the distant magnetotail (~90RJ). We have now added a few sentences to clarify this matter.

Reviewer #2 Evaluations:
Recommendation: Return to author for minor revisions
Significant: Yes, the science is at the forefront of the discipline.
Supported: Mostly yes, but some further information and/or data are needed.
Referencing: Yes
Quality: Yes, it is well-written, logically organized, and the figures and tables are appropriate.
Data: Yes
Accurate Key Points: Yes

Reviewer #2 (Formal Review for Authors (shown to authors)):

This manuscript provides the first Juno observations of "dawn storms" in the jovian magnetosphere/ionosphere, especially on the nightside, based on time series of Juno-UVS images. The measurements showed the development of several dawn storms from the initial stages to the end, including the dynamic evolution of the nightside jovian aurora all the way to the dayside aurora using the first 20 orbits of Juno. These observations of nightside jovian aurora were impossible in previous jovian magnetosphere/auroral studies based on HST images alone. These new results show that, quite similar to terrestrial substorms, the evolution of the jovian aurora indicates transient magnetospheric reconfiguration and substorm-like responses in giant magnetosphere, although the temporal and spatial scales are different (of course!). The observed dynamic, transient evolution of jovian aurora apparently cannot be explained by the well-known hypothesis - the over-simplified corotation breakdown theory - which dominates the understanding of magnetospheric dynamic and aurora in fast rotating, giant magnetospheres.

Besides the development of "isolated" dawn storms, these Juno observations also showed cases such as non-isolated dawn storms in the jovian magnetosphere, together with pseudo-breakup cases, both are seen in the terrestrial magnetosphere corresponding to different modes of convection. Despite the fact that the amount of mass loading and energy transfer in the magnetotail of Earth and Jupiter are completely different, the Juno auroral observations showed magnetospheric invariant here - the auroral signatures of the processes releasing particle/energy at Jupiter are remarkably similar to terrestrial auroral substorm, regardless of their differences in the size, time scale and rotation speed.

These results are significant contributions to the understandings of magnetospheric physics, especially they are based on observational evidence, although the detailed processes driving/related to the dynamic evolution is still unknown/debatable. This study enables discussions on refining/re-define the physical picture of giant magnetospheres and will potentially draw attention from the broad space science community. The jovian magnetosphere is thought to be mostly different from terrestrial magnetospheres driven by the upstream conditions, while the jovian magnetosphere is regarded as driven by internal processes. These new observations show that planetary space environments share remarkable similarities, which was not recognized/appreciated in previous studies on comparative planetary magnetospheres. The reviewer enjoyed reading the manuscript very well, which is well organized with clear figure descriptions and discussions, including references to related literature from both planetary and terrestrial magnetospheric studies. The manuscript is a significant advance in our understandings of comparative planetary sciences and should be published in AGU Advances.

The reviewer has a couple of minor suggestions to possibly improve the manuscript.

When talking about aurora processes in giant magnetospheres especially the jovian system, the large-scale current system associated with the corotation breakdown process is usually hypothesized as the driver of the main aurora, which is partially the reason why the jovian dawn storms that resemble terrestrial magnetospheres look so unique. However, if compared to the "main" aurora at the Earth's magnetosphere - mostly diffuse aurora - the majority of the emission power is not related to the large-scale current system [e.g., Korth et al., 2014]. Therefore if working the other way around, the "driver" could not be applied to the geospace (only to a portion of the upward R1 current region on the duskside due to the constraint of current continuity) since aurora acceleration and generation of field-aligned currents are different physical processes. The leading authors have recently published an important paper providing observational evidence against the hypothesis of corotation breakdown as the driver of aurora at giant magnetospheres, which seemed to be consistent with this argument. Therefore, the authors may think about including short discussions on the validity of using large-scale FACs as a proxy for auroral precipitation, especially on the fact that corotation breakdown hypothesis cannot be applied to these transient energy release processes associated with auroral precipitation observed in the jovian magnetosphere (in fact it may not be directly related to most of the auroral processes in the jovian magnetosphere at all).

Thank you very much for making this excellent point and for bringing this reference to our attention. We could not agree more with the reviewer: the explanatory power of large scale field aligned currents is limited and dawn storms are another example showing that other mechanisms should be considered. We have added a short paragraph arguing in that sense at the end of the discussion.

The authors speculated physical processes that are possibly related to the initiation of the auroral breakups, including ballooning, interchange and current-driven instability. It may be worth mentioning that the shear flow-ballooning mode, which unifies both the KH and interchange instabilities in such a fast-rotating magnetosphere [Viñas and Madden, 1986], can excite plasma waves in the inner magnetosphere what may modulate the morphology of the aurora beads/emissions.

Thank you for bringing this paper to our attention. We now also refer to the shear flow ballooning instability in the paper and cite Viñas and Madden (1986).

Korth, H., Zhang, Y., Anderson, B. J., Sotirelis, T., and Waters, C. L. (2014), Statistical relationship between large-scale upward field-aligned currents and electron precipitation, J. Geophys. Res. Space Physics, 119, 6715- 6731, doi:10.1002/2014JA019961.

Viñas, A. F., and Madden, T. R. (1986), Shear flow-ballooning instability as a possible mechanism for hydromagnetic fluctuations, J. Geophys. Res., 91( A2), 1519- 1528, doi:10.1029/JA091iA02p01519.

Reviewer #3 Evaluations:

Recommendation: Return to author for minor revisions
Significant: Yes, the science is at the forefront of the discipline.
Supported: Yes
Referencing: Mostly yes, but some additions are necessary.
Quality: Yes, it is well-written, logically organized, and the figures and tables are appropriate.
Data: Yes
Accurate Key Points: Yes

Reviewer #3 (Formal Review for Authors (shown to authors)):

This paper is excellently written and worthy of prompt publication. It is the first report to provide the global description of dawn storms in Jupiter's aurorae, from their initiation to their end. The work is comparative planetology, where the authors have compared their observations at Jupiter to observations at Earth. These types of studies help us probe and better understand physical processes that affect us more directly here in geospace.

I only have extremely minor suggestions that do not require my review in a second round.

Minor Comments:
Figure 2: The red and purple text is hard to read. I know this is to correspond to Figure 5, but if a brigher red and purple shade could be used it would be very helpful.

We agree with the reviewer that the readability of the annotations in this figure should be improved. We tested different strategies, including using brighter shades of red and purple, but we concluded that the best results were obtained by using bold fonts and semi-transparent backgrounds to enhance the contrast.

Figure 4: It's not a deal-breaker, but I wonder if authors could rotate the images so that the sun is always pointing in the same direction? I feel it would help the reader interpret the rotation of the storm better. At first I thought it was rotating the wrong way, and then I realized the reference frame was consistently changing.

The reviewer is right to notice that we oriented the polar projection with the Sun up for all our figure but this one, which is needlessly confusing. We now use the same local-time-fixed reference frame all across the paper for more consistency.

Line 342: Authors may also want to check out Panov et al., 2020, and references (e.g., Panov et al., 2019) which discuss these interchange ballooning type instabilities:
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020JA027930

These papers may help provide even more context.

We now cite this paper.