

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

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Author Response to Peer Review Comments

**Peer Review Comments on 2020AV000275**

**Reviewer #1**

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 terrestrial "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".

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 a 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.

#### 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!

Line 175: The the

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

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.

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

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

Lines 330-331: Describe in specific detail what is meant by "outside-in" vs. "inside-out". This isn't clear. Perhaps it is necessary to 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.

## **Reviewer #2**

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 invariance 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).

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.

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**

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 brighter red and purple shade could be used it would be very helpful.

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.

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.