Plasma Structuring in the Polar Cap - Definition, Generation Mechanisms, and Properties of Polar Cap Patches: Discussion and Important Future Research Areas

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This session examined polar cap patches and other density enhancements in the polar cap with the goal to reevaluate how we define patches and whether or not that definition is scientifically useful. In particular, we discussed a variety of different mechanisms that may generate density enhancements in the polar cap and whether or not they are in fact distinct phenomena, and if so, if they are likely to be mistaken for polar cap patches (or vise versa).

Phenomena that are likely to cause density enhancements in the polar cap:

- **"Classical" Polar Cap Patches:** Regions of densely ionized dayside plasma that are dragged into the polar cap through the cusp and separated through fast flow channels driven by bursty reconnection at the magnetopause and movement of the X-line. These create "islands" of dense dayside plasma that are generally accepted to be between

50-500 km across, move with the background plasma convection (anti-sunward through the center of the polar cap for negative IMF Bz), and are elongate in the cross-track direction ("cigar shaped"). These patches have traditionally been defined as twice the background density.

- **"Hot" Patches:** Density enhancements of a similar morphology and size to "classical" polar cap patches, but hotter than the background plasma (instead of cooler). These are thought to be caused by soft precipitation.
- **Tongue of Ionization (TOI):** A "tongue" of densely ionized dayside plasma stretching deep into the polar cap. This is generated by dayside plasma being pulled into the polar cap by the background convection, similar to with "classical" patches, but it maintains its integrity as a single structure instead of being cut into patches.
- **Gravity Waves (GW):** Atmospheric gravity waves generated from the secondary or tertiary dissipation of mountain waves, or generated by the polar vortex, can travel across the polar cap. These are neutral atmospheric phenomena driven exclusively by thermospheric activity. Due to filtering based on the direction of the polar vortex, these waves travel preferentially sunwards across the polar cap. Although, there are instances where GWs can travel different directions, or not exactly sunwards.
- **Traveling Ionospheric Disturbances (TID):** Large-scale wave-like structures that have been observed propagating along the same direction as 2-cell convection in the polar cap. These are potentially generated from heating in the cusp region. They are typically lower amplitude than "classical" patches but may approach the "double the background" value during intense storms.
- **Sun-Aligned Arcs (SAA):** Auroral structures in the polar cap that typically extend along the sun-earth line. These are generally associated with northwards IMF Bz, and are also known by the terms "polar cap arc" or "theta aurora".
- **Polewards-Moving Auroral Forms (PMAF):** Auroral structures that may move into the polar cap and act as patches. A reservoir of dense plasma is heated and transported to the F-region through upwelling, and is then convected into the polar cap.

In general, "classical" polar cap patches can at least be described as a discrete phenomena from many of these other processes, however there is definitely still debate as to the extent to which patches and TOIs are different processes, vs subcategories of the same general process of transporting highly ionized dayside plasma into the polar cap or different stages in the life cycle of a common process. Furthermore, it is not entirely clear how anti-sunwards-moving TIDs are generated, so it is difficult to say for certain that they are a distinct mechanism vs "patches" that don't quite meet the required "double the background" definition.

There are challenges with defining polar cap patches simply as "a density enhancement twice the background". Many of the phenomena listed above have the potential to generate a density enhancement following that definition, so statistical studies using only that definition are likely to mix together enhancements from a variety of mechanisms. Potential other considerations for a "classical" patch definition could include:

- *Temperature:* Enhancement that are "hot" may be more likely to be generated from precipitation ("hot" patches, SAA, or PMAF) rather than dayside plasma transported into the polar cap
- *Motion:* Patches are expected to move with the background convection while GW and TID are likely to have a propagation direction relative to the background convection.
- *Polar Cap Boundary:* Many studies use a hard latitude cutoff to define the polar cap, but we know the auroral oval and open-close boundary is dynamic. Without considering this, it may be very easy to confuse an auroral structure for a polar cap patch.

The nuances of these definitions are increasingly important as we look more towards using automatic detection algorithms to do studies of patch (and other polar cap phenomena) dynamics over multi-year long datasets. Additionally, there are concerns about instrument-specific definitions. The density definition may not work well for airglow observations for instance because density is only one factor in airglow brightness. Some instruments have vastly different spatial coverages and resolutions (ie, ISRs and GNSS TEC) which may bias the number of patches identified depending on the definition used.

The phenomena listed above that are not "classical" polar cap patches also merit further study. Many of these phenomena have the potential to interact with each other and "classical" polar cap patches in ways that could create very complex dynamics. At present, there does not appear to be compelling evidence to disregard any of these phenomena as negligible, although careful statistical studies may help determine if some are more dominant than others under certain conditions. Any such study would have to be extremely careful with the definitions and observing modalities used to distinguish phenomena from each other.

An operational definition of patches may be useful in the future that identifies only patches that may cause HF propagation deviations or transionospheric scintillation. These are likely to only be the largest patches with the sharpest edge gradients or substantial internal structuring that may seed the gradient-drift instability and structuring cascades. While identifying these patches may be operationally useful, a lot can still be learned scientifically about high-latitude dynamics from smaller or less dramatic density enhancements.

Several open questions came up during the presentations and subsequent discussions:

- What exactly is the process by which patches are segmented off from the dayside plasma into discrete chunks and why don't current numeral models reproduce this?
- How and when do different polar cap structuring phenomena interact with each other?
- Is there a dominant mechanism responsible for the majority of polar cap structuring?
- What is the distinction between "hot" patches, SAA, and PMAF?
- How do we define background so we can then classify how large enhancements are above it? "Background" in the polar cap is extremely seasonally and diurnally dependent and true "quite" periods are rare.
- What is the precise process that launches TIDs into the polar cap?

The following topic and activities were identified as areas that could help address some of these questions:

- **High resolution simulations of both the thermospherics and magnetospheric impact on the high-latitude ionosphere simultaneously.** Waves have been modeled propagating with only influence from one or the other, so it is unclear which (if either) is the stronger driver and how they might interact with each other. The MAGE framework will likely be attempting this in the near future.
- **High resolution maps of high latitude convection.** Simulations have shown magnetospheric-driven convection can be extremely complex and highly structured at mesoscales, which produces a twisted and warped TOI, but have not been able to cleanly replicate cross-track elongated patches. Enhanced high-resolution SuperDARN convection maps may help determine the expected mesoscale details in the convection pattern and better inform how it interacts with dayside plasma.
- **More and higher-resolution high-latitude imaging capability.** There is currently a lack of complete observations showing the auroral zone, cusp, and entire interior of the polar cap, particularly simultaneously or over long enough periods of time to watch structures evolve. This may be challenging to achieve over the entire polar cap because GNSS satellites do not orbit at a high enough inclination to cover this region and observations from existing GNSS receivers are highly oblique. Returning the RISR-N/C to full capability may help with this. There will likely also be the opportunity in the next few years to instrument RBO; some consideration should be given as to what observations will be the most useful.
- **Studies investigating the statistical properties of mesoscale structuring in the polar cap.** Because many of the patch phenomena are expected to be quasi-random, point-to-point comparisons between numerical models and observations are expected to be futile. It would be better to focus on defining the characteristic time and spatial scales, and how these change over time and with different conditions, and see if they can be replicated by a model instead of trying to reproduce an exact stream of patches. It may be tricky to run a high-resolution regional model long enough to get the requisite statistics.