

Sunlit Aurora, Substorms and Ion Upflow

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Introduction

Sunlit aurora, a signature of high-altitude N2+ populations, is unique in that it is not produced by electron precipitation but by solar UV photons.

- First reported by Carl Störmer in 1929, with most of his work being focused on its morphology and occurrence statistics, noting in particular its extremely high altitudes of 800 km or higher.

- These early observations noted a correlation between sunlit aurora and electron-driven aurora.

- Here, we show images of sunlit aurora from a fortuitous event in northern Norway, captured on a cellphone camera. The sunlit portion of the aurora appeared in the skies *above* a region of green (557.7 nm) aurora in one photo and in conjunction with other wavelengths in the other photo.

- The RENU3 rocket, launched in 2025, carried a new mass spectrometer that provided relative measurements of O+ to N2+, O2+ and/or NO+ (potential sunlit populations). While the O+ population is nearly an order of magnitude greater than the molecular species, the instrument does show clear measurements of these species, further linking the potential sunlit populations to O+ ions.

- Given the abundance of work that has shown ion upflow resulting from Joule heating (Type 1) or from soft electron precipitation (Type 2), we suggest that sunlit aurora is a byproduct of ion upflow and point to features in the 2 photos that strongly support this.

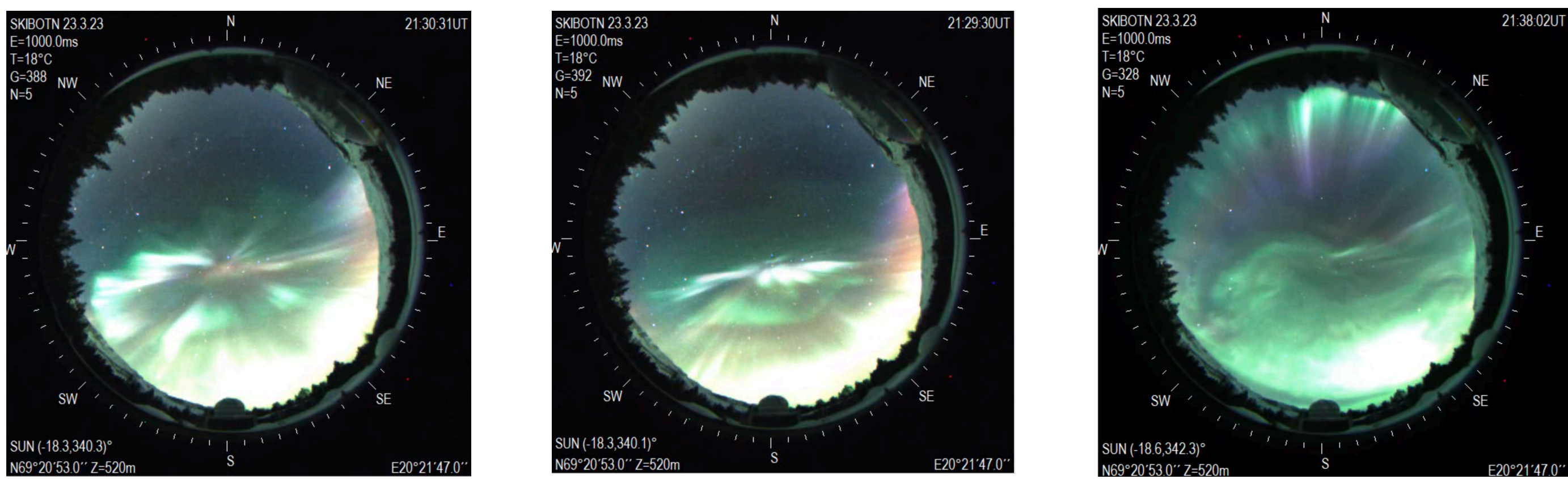
Event Description



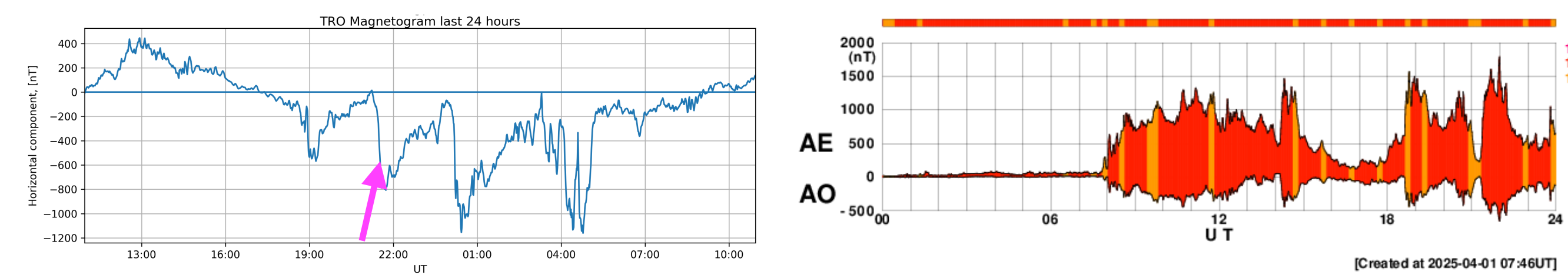
This figure shows photos during the event, photographed by Sunniva Hansen of Andøya Space. The image on the left was taken on March 23, 2023, at 10:30 PM (local time) or 21:30 UT, which is just after magnetic midnight. The image on the right was taken a minute earlier, at 21:29 UT. Both images were acquired using Samsung Galaxy S21 Ultra with settings of ISO400, 12MP, F2.2 and a 20 sec exposure.

In the image on the left, note the presence of blue (427.8 nm) emissions above the green (557.7 nm) emissions. In the image on the right, we see high-altitude blue emissions but with red (630.0 nm) emissions beneath it. We'll return to this point...

Note that the blue emissions (427.8 nm from N₂⁺) are higher in altitude than the green emissions (557.7 nm from O⁺), excited by precipitating electrons). We emphasize that these emissions are from *two different species that were driven by two different processes*.



These images are from the BACC camera in Skibotn (near Trømsø). The images in Fig 1 are near the center of the FOV in the left and center images here. The image on the right is from ~10 minutes later shows a large region of sunlit aurora.



Data from the Tromsø magnetometer H-component on the left. Four “negative bays” occurred late in the day and into the early hours of the next day, indicative of substorm onsets. The second onset occurred at ~21:10 UT, which is the start of the substorm during which the photo was taken. The plot shows that the substorm negative bay reached a peak of approximately 800 nT. It was a biggie substorm. The panel on the right shows the AE index for the entire day, again showing exceptional activity.

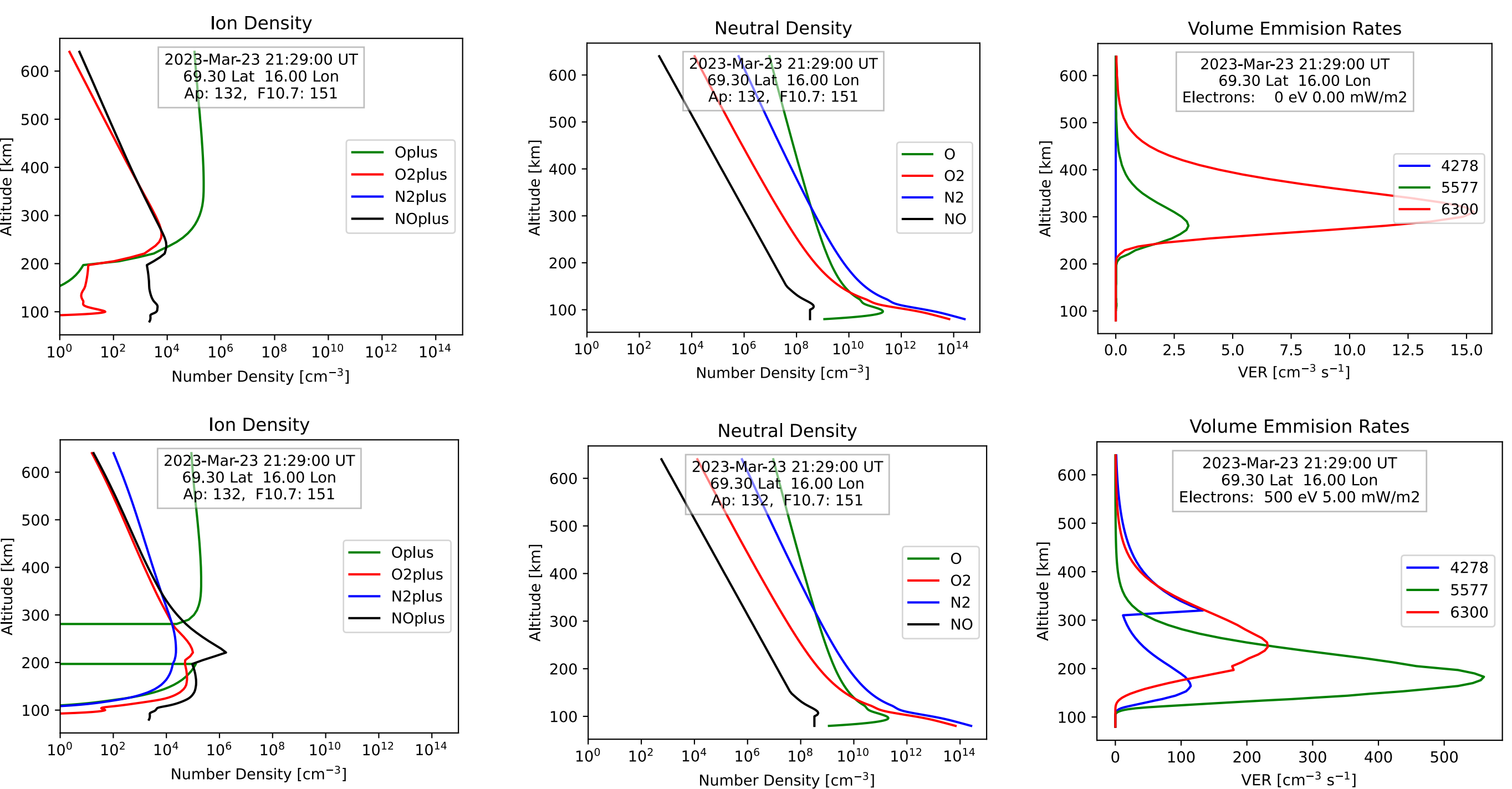
Ion Upflow Discussion

So, just how do molecular ions end up at these very high altitudes? This is a fundamentally important question!

A key point is that ion upflow (which potentially leads to ion outflow, meaning those ions that can escape Earth's gravity) can be initiated by either ionospheric Joule heating (Type 1) or by soft-electron precipitation (Type 2). In addition, however, Sadler et al. [2012] (also see Sadler et al. [2026]) present numerical results showing how ion upflows can couple, via momentum exchange, to neutral upwelling during a soft-electron precipitation event, though the ion-neutral coupling would likely also be effective in a Type 1 event.

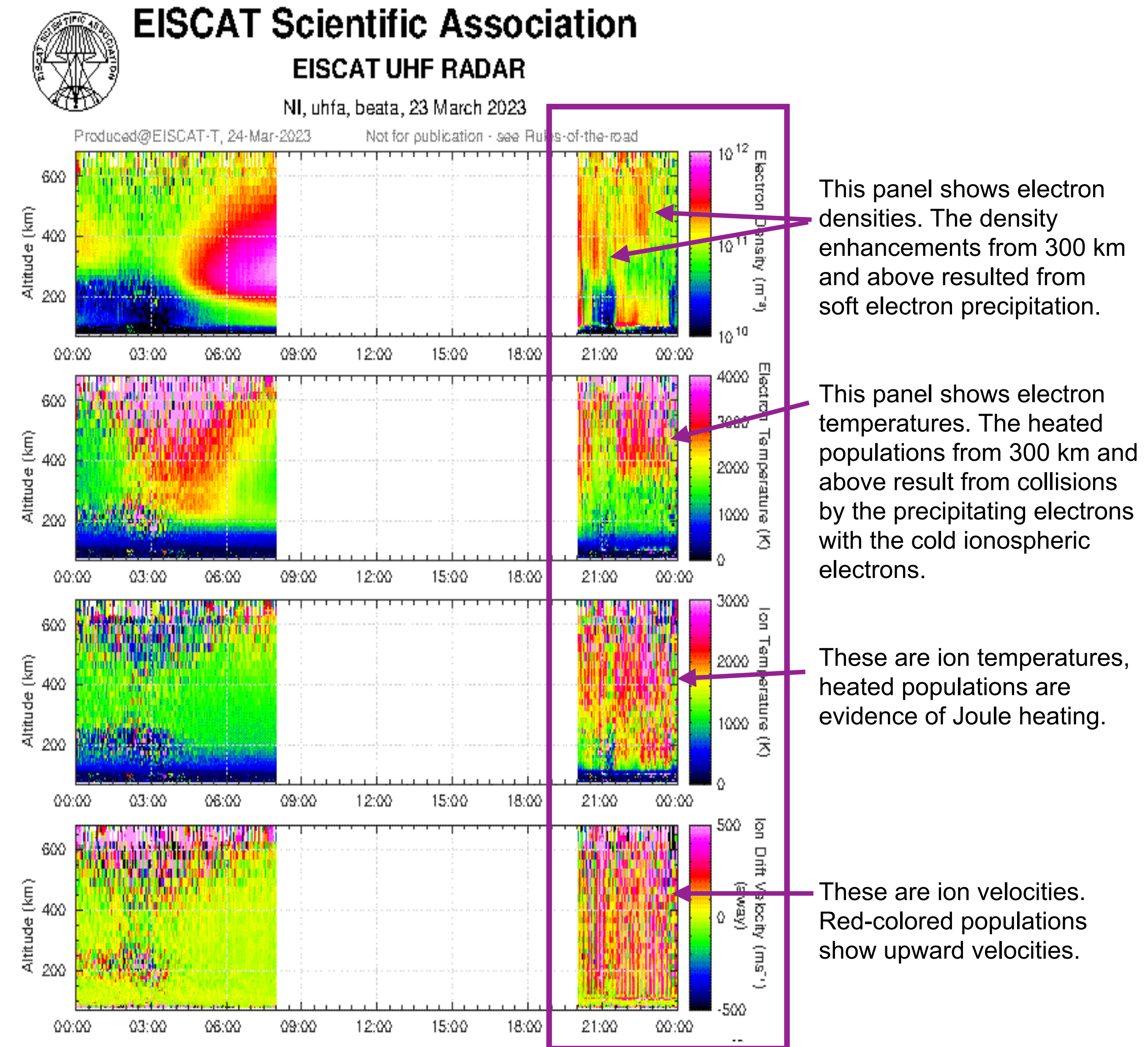
Is a link between sunlit aurora and ion upflow reasonable? Below, we show GLOW model results for this event. The top row shows profiles of ion density, neutral density and volume emission rates with no precipitation (i.e., it is a baseline quantity). The second row shows the effects of precipitation of 5 mW/m² at 500 eV (an exceptional energy flux level).

Note that neither case shows the presence of significant ion densities at high enough altitudes that could lead to sunlit aurora. The panel at the lower right does show that soft precipitation can drive sunlit aurora, however this precipitation is also known to drive ion upflow. Note that GLOW does not incorporate transport effects and, therefore, do not show ion upflow dynamics.



EISCAT Radar Perspective of Ion Upflow

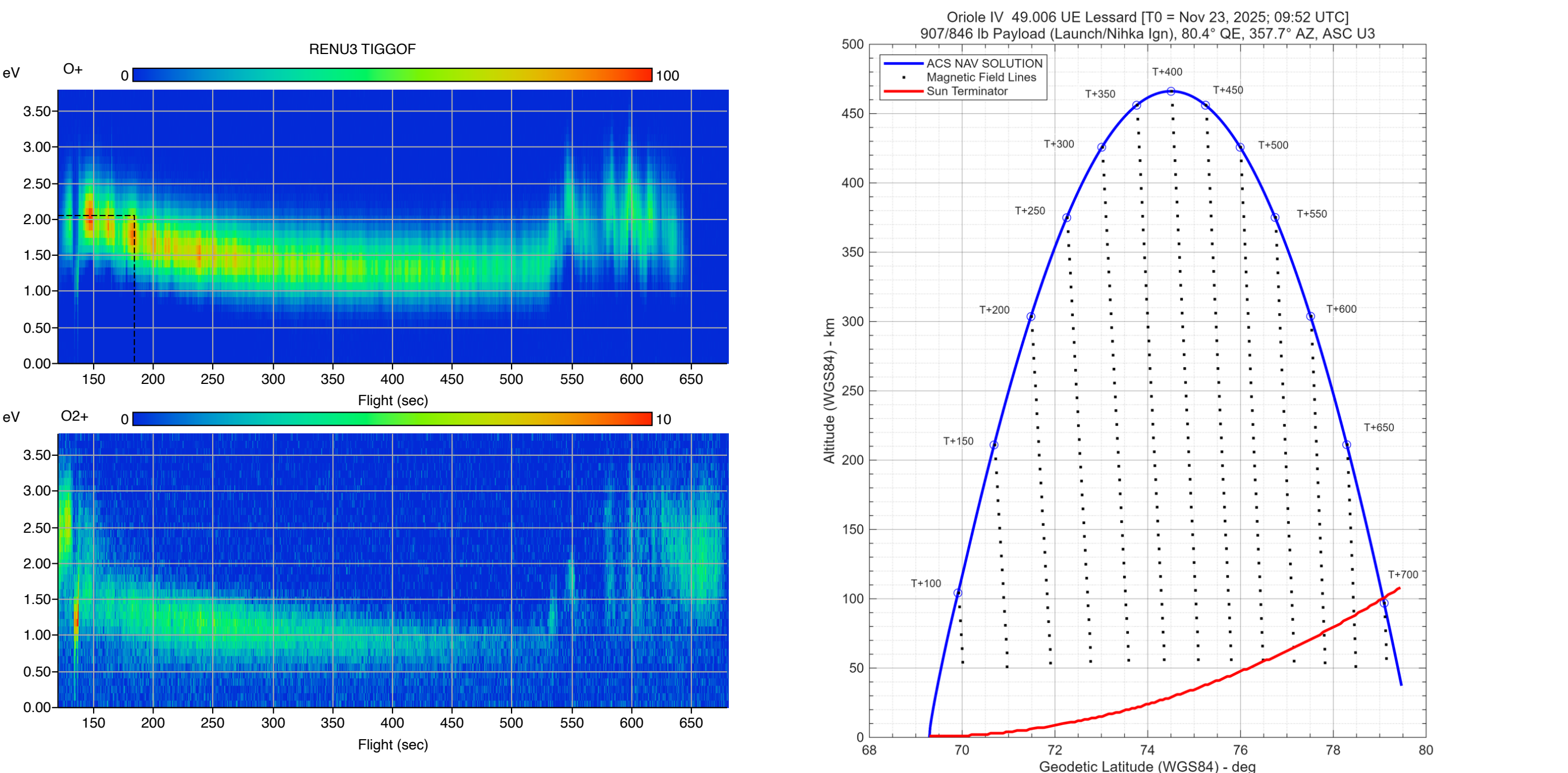
EISCAT UHF Radar data from Tromsø is shown below, for the entire day (except for the huge gap in the middle, of course). The data clearly show electron density and heating enhancements (top two panels) at the same time as ion heating and upflow speeds of hundreds of m/s. This is an intense (but classic) case of simultaneous Type 1 & 2 ion upflows.



RENU3 rocket data

The data presented here was acquired by the Rocket Experiment for Neutral Upwelling 3 (RENU3), launched on Nov 23, 2025 @ 09:52 UTC from Andenes, Norway. This was a cusp (dayside) launch, although ion upflow processes on the day versus night side involve the same physical processes. The RENU3 launch was also an upwelling event and reached an apogee of 466 km before descending through the cusp region.

The top panel shows O⁺ ion energies versus time-of-flight. The bottom panel shows O₂⁺ and/or N₂⁺. The heating starts as the payload reaches ~380 km (T+530) on the descent; the composition change to being 95% molecular species occurs about 250 km (T+640).

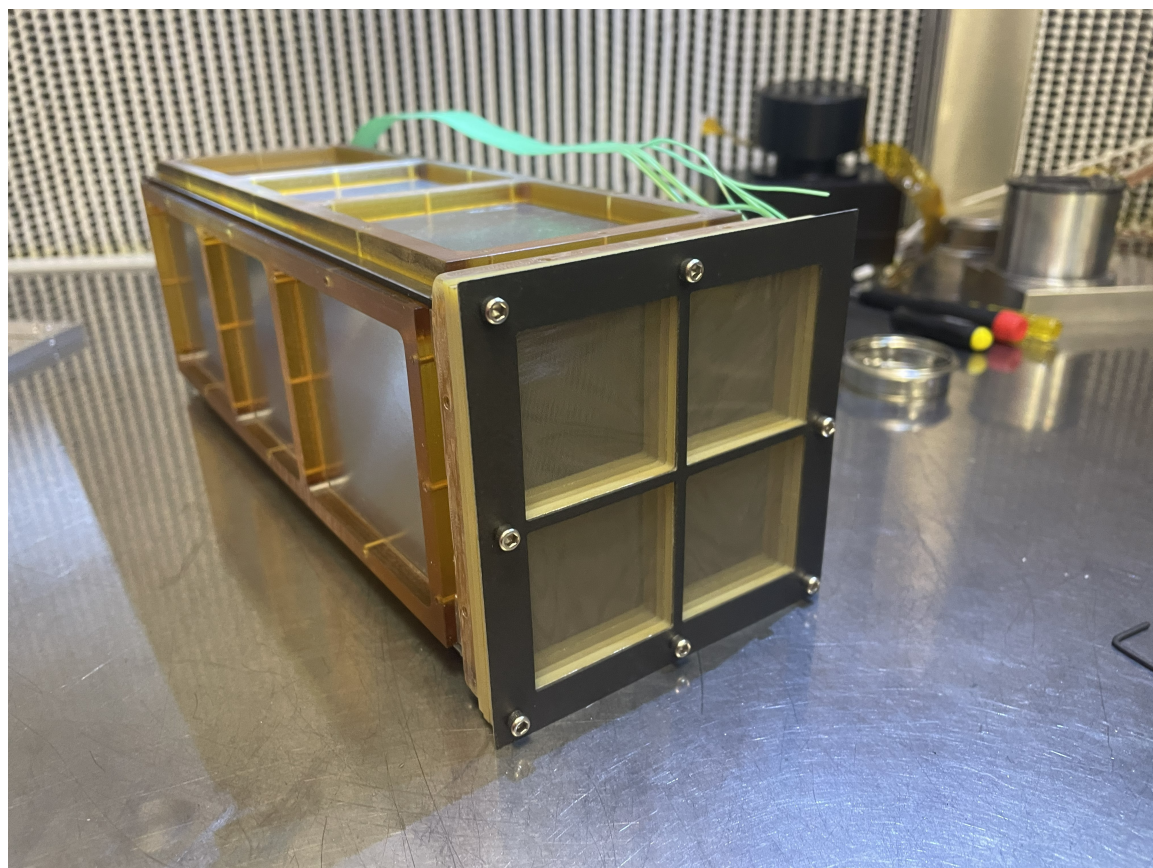


Thermal Ion Gated Time-Of-Flight (TIGTOF) mass spectrometer

1. Uses a gated Time of Flight (TOF) method to measure ion mass (and fluxes of individual ion species within a population).

2. Process is controlled by the four concentric screens across the instrument aperture, including a ground, electron rejection, selection, and acceleration screens.

3. Selection screen voltage sweeps through the allowed energies (0.006 eV to 6 eV, with 0.06 eV resolution) and also toggles (on/off every ≈12 μs) in order to admit or reject incident ions.



Summary

We show two images of sunlit aurora occurring during an intense substorm. Most other reports of sunlit aurora focus on dayside activity; we are not aware of other reports of sunlit aurora that are clearly part of a substorm.

- The fundamental question of sunlit aurora regards the process that lifts the N₂⁺ ions to these very high altitudes.

- A potential link between ion upflow and sunlit aurora has been discussed in a few papers (Ilie et al. [2023], Ellingsen et al. [2020], Ilie and Liemohn [2016]).

- The activity during the event (see EISCAT data) shows support for both Type 1 and Type 2 ion upflow.

- Sadler et al [2012, 2026] show how neutral upwelling can result from momentum exchange in ion upflows. In principle, this should also apply to molecular ions, including N₂⁺.

- The second image shows some red aurora, which is an indicator of soft precipitation (i.e., a Type 2 process). It is very possible that Type 1 processes are also occurring.

- The first image does not show any red aurora, implying that Joule heating must be doing the lifting (Type 1).

- We conclude that sunlit aurora is a fundamental part of ion upflow, whether it is Type 1 or 2.

References

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