Climatology of very high ionospheric electron temperature occurrences as observed by Swarm constellation

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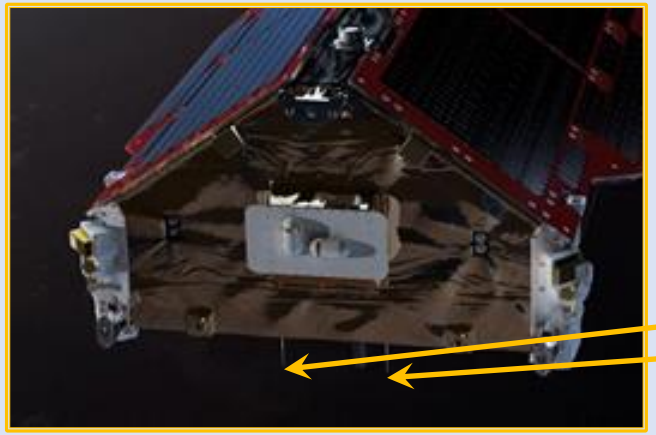
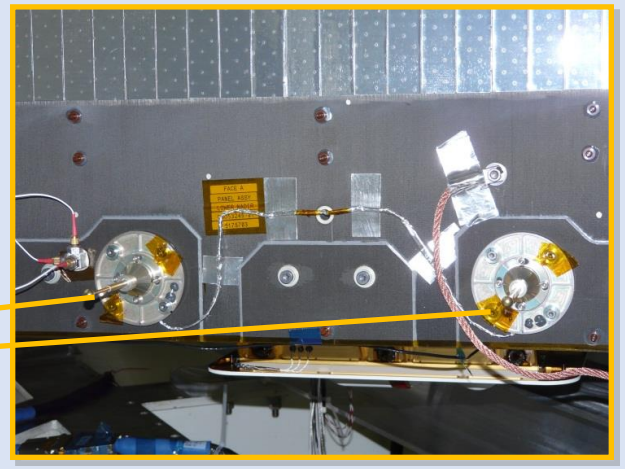
The ESA Swarm constellation is composed by three Low-Earth near polar orbiting spacecraft flying since November 2013, with the main goal of mapping the Earth's magnetic field with unprecedented accuracy.
The two lower satellites form a pair at 460 km height (Swarm A and C), the third (Swarm B) flies at about 520 km height.
More info and references at:
https://earth.esa.int/eogateway/missions/swarm





Each spacecraft also carries a pair of **Langmuir Probes (LP**), part of the Electric Field Instrument (EFI): two sensors (probes), located under the S/C body, which measure: **plasma electron density N_e, electron temperature T_e, spacecraft potential Φ_{SC}**

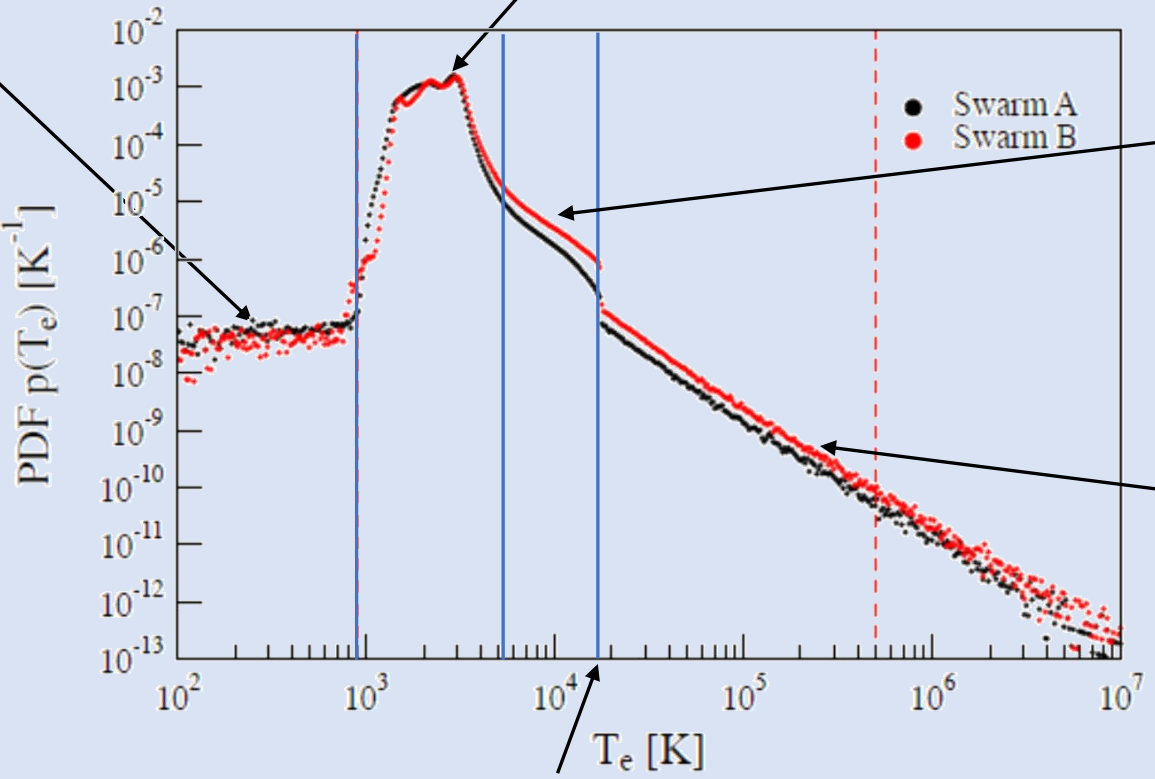
(Knudsen DJ, Burchill JK , Buchert SC , Eriksson A, Gill R, Wahlund JE, Åhlen L, Smith M, Moffat B (2017), "Thermal ion imagers and Langmuir probes in the Swarm electric field instruments", *Journal of Geophysical Research: Space Physics*, Vol. **122**, pp. 2655–2673 https://doi.org/10.1002/2016JA022571 **)**

Swarm Electron Temperature spectral properties

The overall quality of plasma data is good; nevertheless, electron temperature is often affected by innaturally high values (Te > 6000 K). Are such measurements «physical» or are they «instrumental?

Low Te (< 1000 K) flat spectrum

Main Te distribution (1000 < Te < 6000 K): log-normal or double log-normal depending on Lat/LT…



«High Te» distribution (6000 < Te ~ 20000 K): power law + some other more exotic (Weinbull, Fréchet… Under investigation)

«Extreme Te» distribution (Te > 20000 K): power law.

Discontinuity step at 17200 K! Above this value a kind of intrumental cut-off (or, better, filter) seems to occur: higher Te are still detected, but at a much lower rate.

- We analyzed 7 years of Swarm electron temperature data (**04/2014 – 03/2020**), for all spacecraft, and calculated, first of all, the average monthy occurrence of **Te > 6000 K events** along the orbits.

- The orbits have been actually segmented in three parts, as a function of Quasi-Dipole Magnetic Latitude (MLAT) : **High Latitude North** (> 50° MLAT), **Mid-Low Latitude** (< |50°| MLAT) , **High Latitude South** (< -50° MLAT) .

- Results can be seen in the following slide and can be summarized as follows:

  - **Mid-Low Latitude rate is much smaller than high latitude rates for all spacecraft**. The overall average orbit rate of high Te events is about 1 % of the total measurements, with peaks up to 3 %. Such montly peaks seem to become more frequent from 2018 onward.

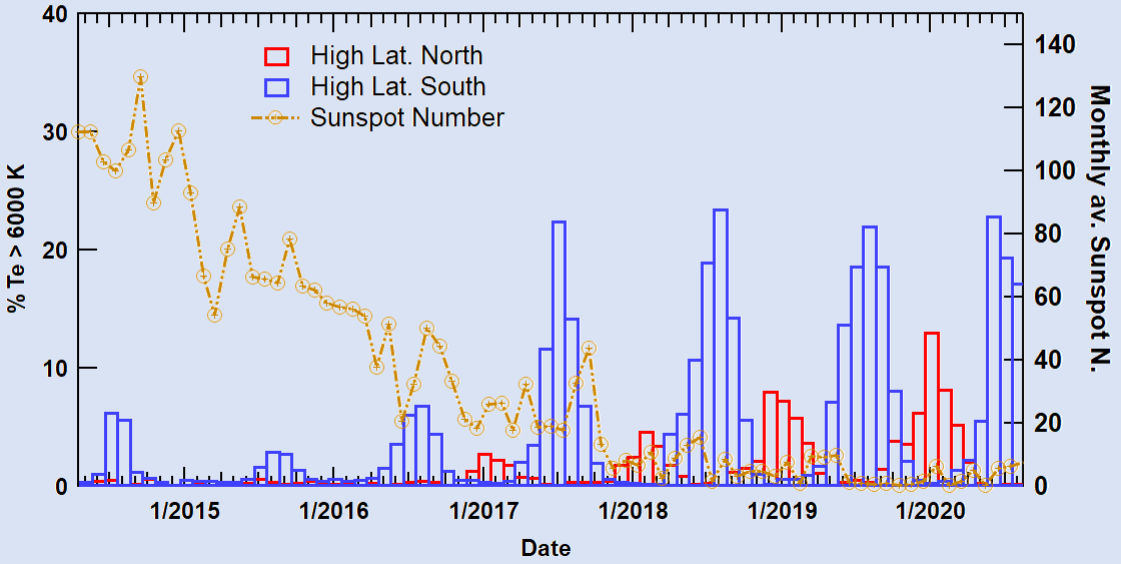
  - There is a remarkable **seasonal effect** for the **high latitude** occurrence of high Te: the % rate maximizes at **local winter times** (June solstice for High-Lat South, December solstice for High-Lat North).

  - The intensity of the rate peaks is **increasing with time, and with the height**, reaching absolute maxima for **Swarm B in June/July 2019 in the Southern Hemisphere**, when the % of high Te could reach, on average, about **38%** of the total measurements.

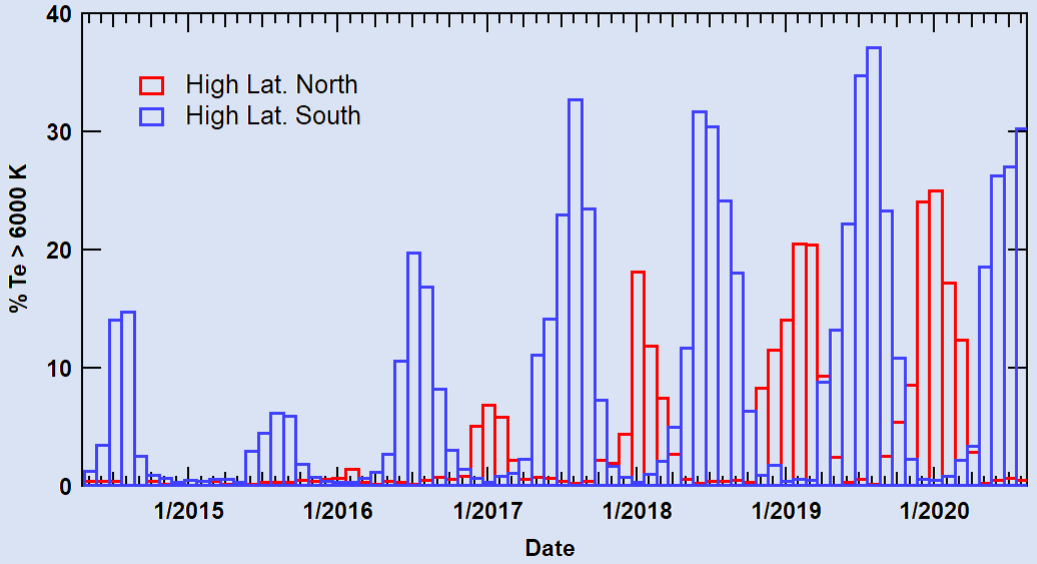
  - The Southern hemisphere always measures higher rates than the Northern one.

  - Solar cycle anti-correlation with high Te rates? This is, for now, only a hypothesis…

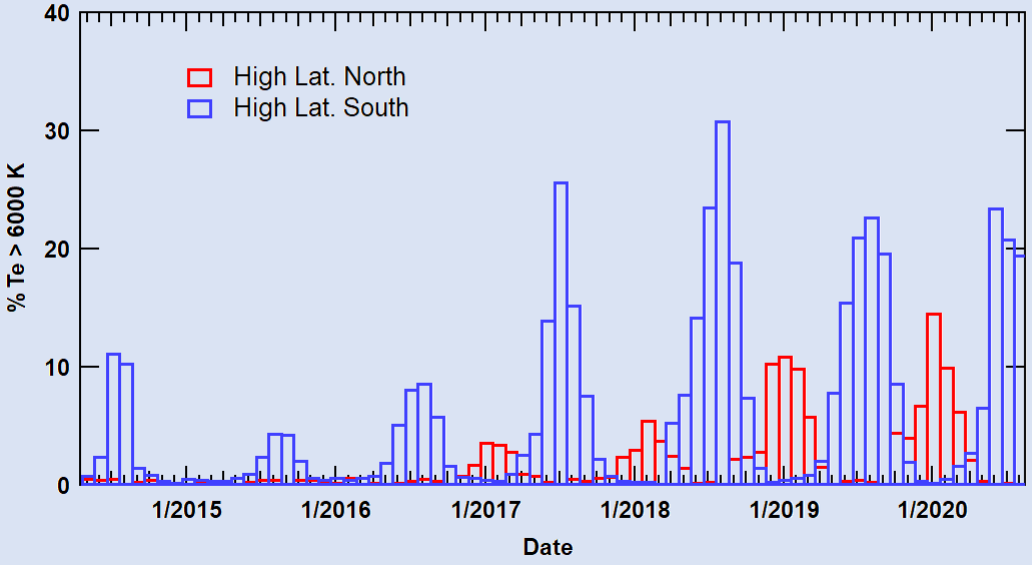
Swarm A, 04/2014 - 08/2020, Te > 6000 K, Monthly orbit average



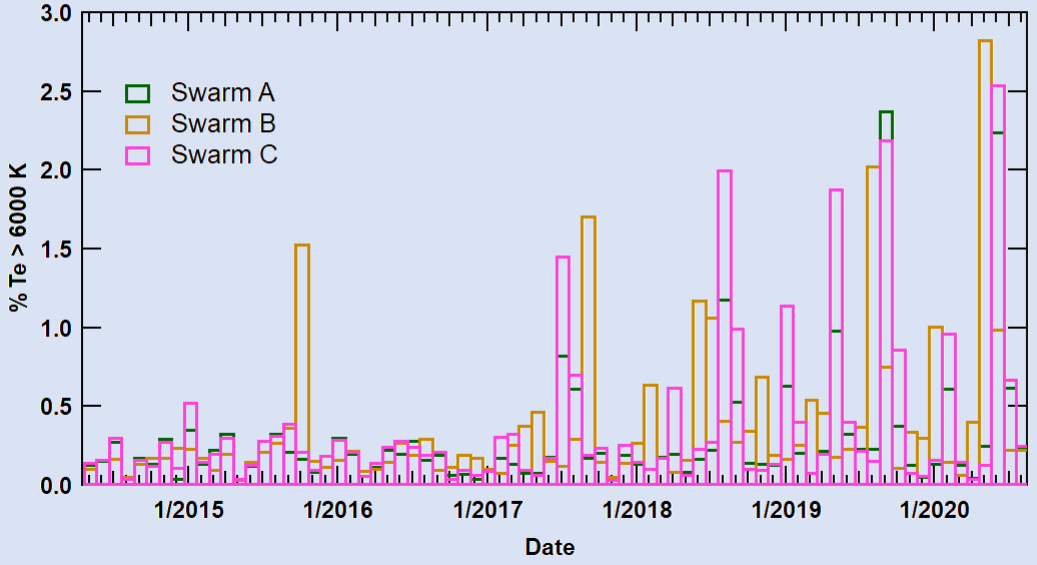
Swarm B, 04/2014 - 08/2020, Te > 6000 K, Monthly orbit average



Swarm C, 04/2014 - 08/2020, Te > 6000 K, Monthly orbit average



Mid-Low Lat., 04/2014 - 08/2020, Te > 6000 K, Monthly orbit average



- Considered the first results from the orbit average, we looked in more detail at the actual distributions of Te > 6000 K considering only the superposed epochs of: **High Lat. Winter** (June+July for the South, December+January for the North), **High Lat. Summer** (the opposite), **Mid-Low Lat. Summer/Winter** (June+July/December+January, meaning Summer/Winter of the Northern hemisphere).

- Calculated averages of: 1) **% rate of Te > 6000 K** with respect to the whole measurements; 2) **average Te values** in the subset of Te > 6000 K; 3) **average values of electron density, Ne**, in the subset of Te > 6000 K, in «pixels» of 1° MLAT x 15 minutes Magnetic Local Time. The same three magnetic latitude macro-sectors of the orbit average analysis are separately shown in the following slides.

- The analysis has been done for all spacecraft, but results are shown in the following only for **Swarm A** and **Swarm B**. Results for Swarm C are very similar to those for Swarm A.

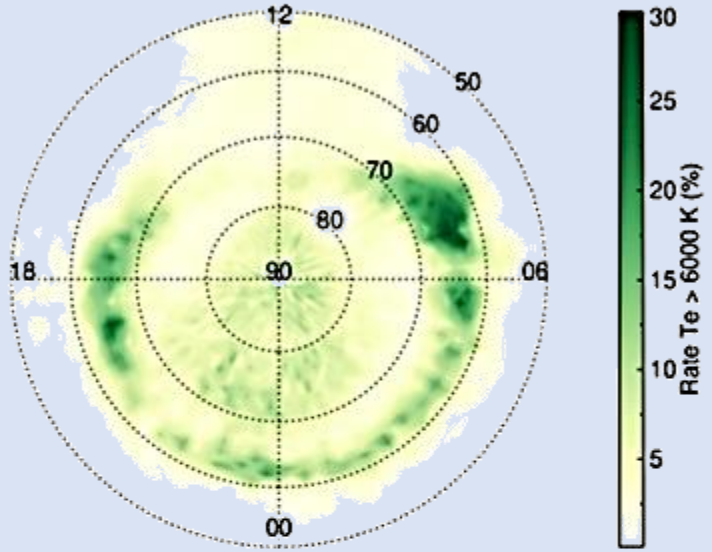
Swarm A, 2014 – 2020, Winter time

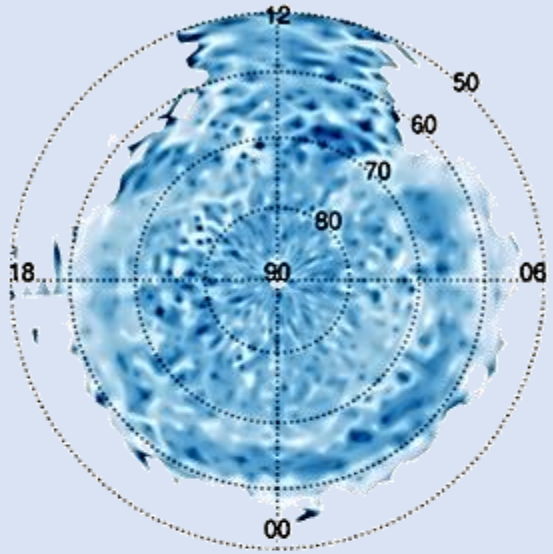
% Rate of Te > 6000 K

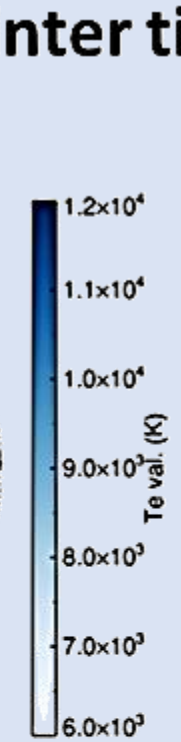
Te > 6000 K distribution

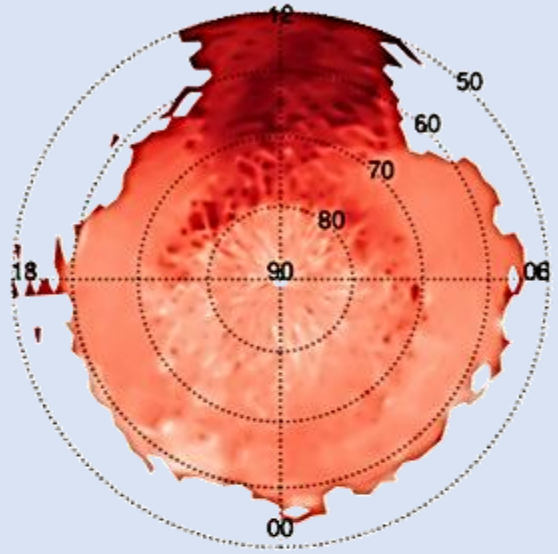
Log(Ne) distribution for Te > 6000 K

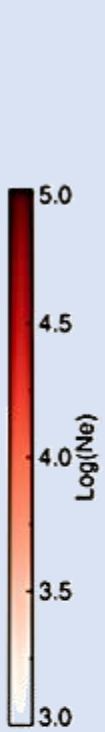
North



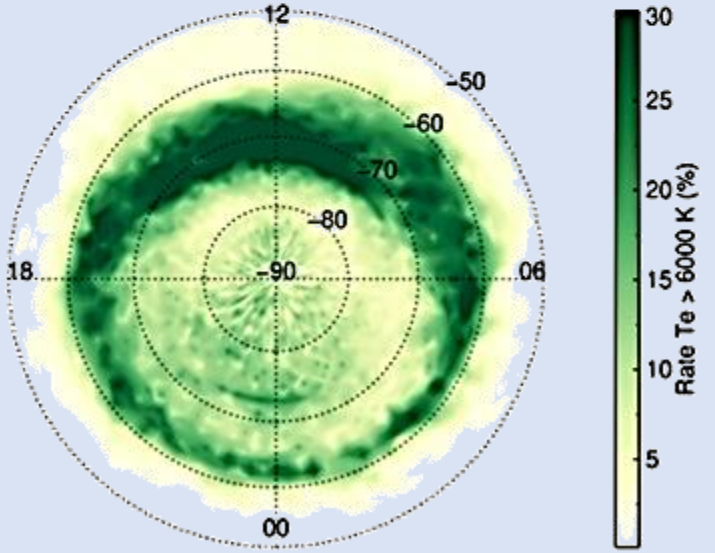


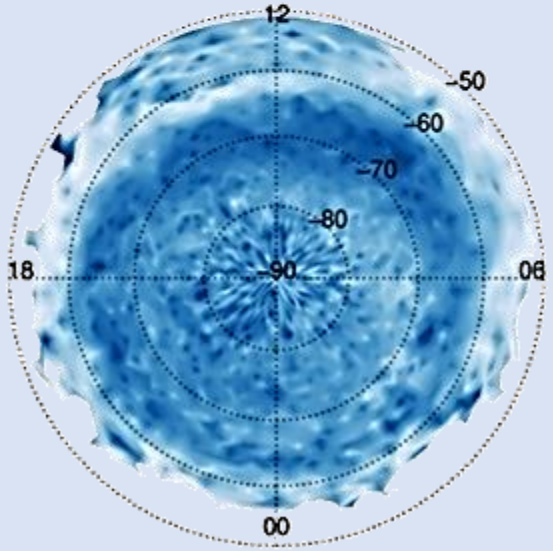


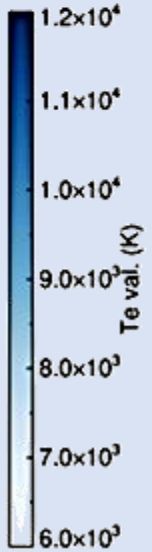


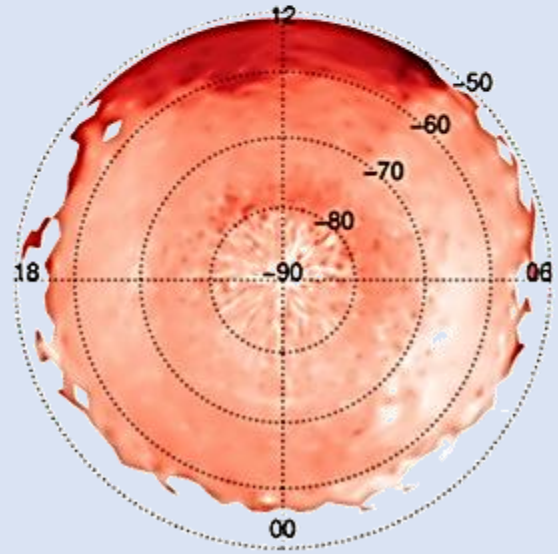


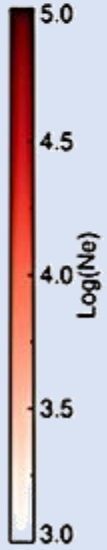
South











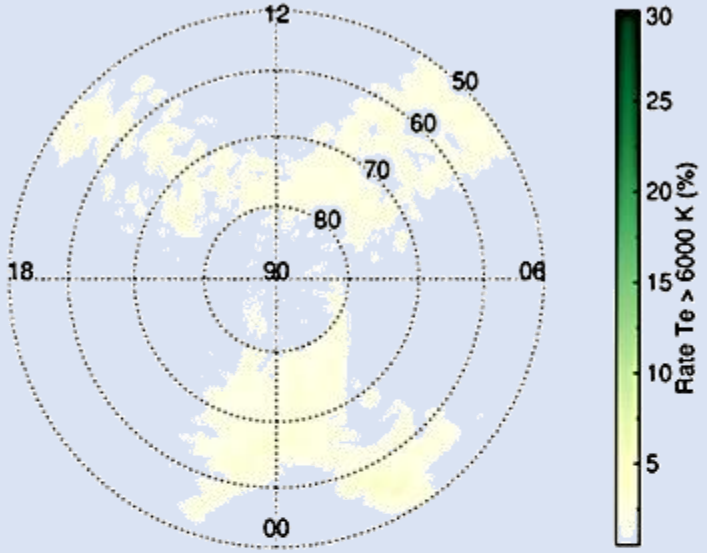
Swarm A, 2014 – 2020, Summer time

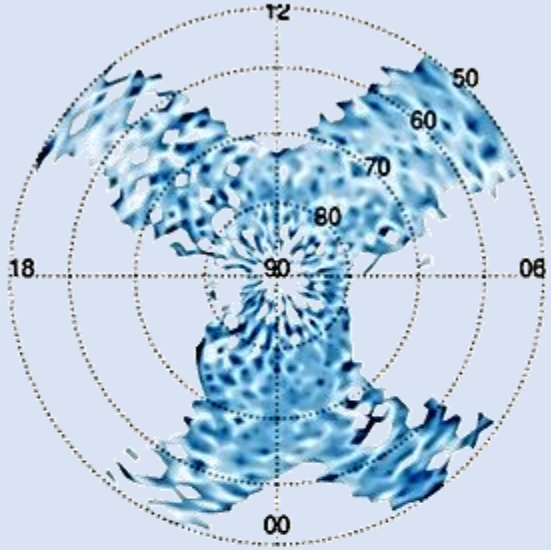
% Rate of Te > 6000 K

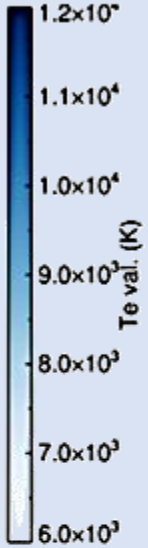
Te > 6000 K distribution

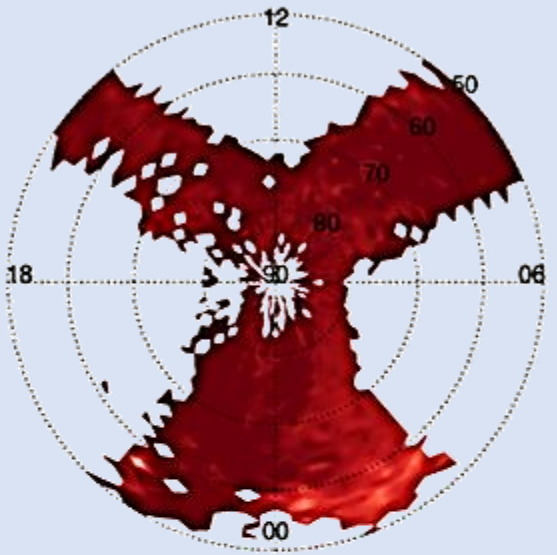
Log(Ne) distribution for Te > 6000 K

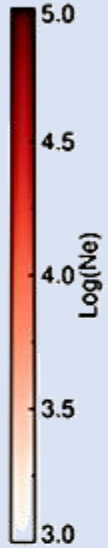
North



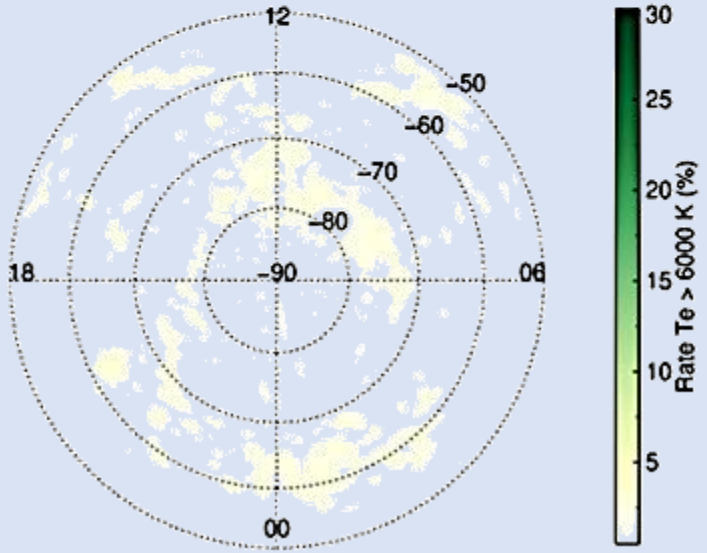


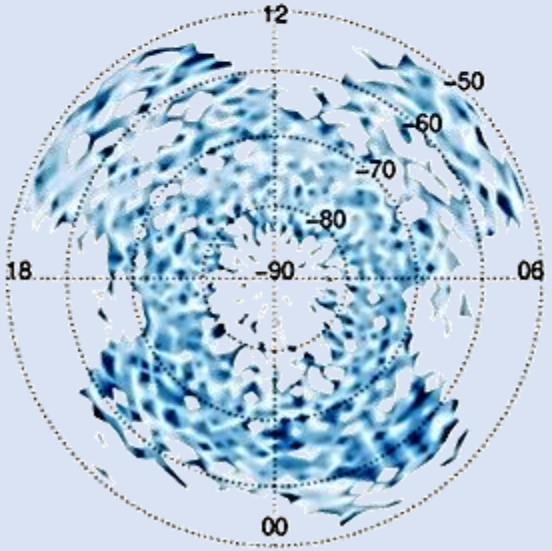


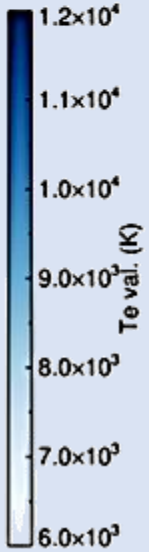


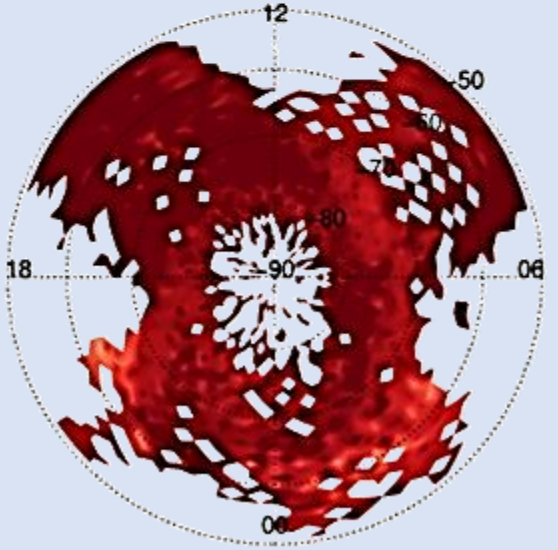


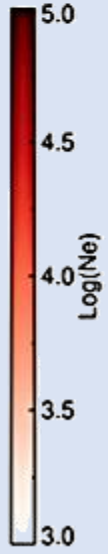
South











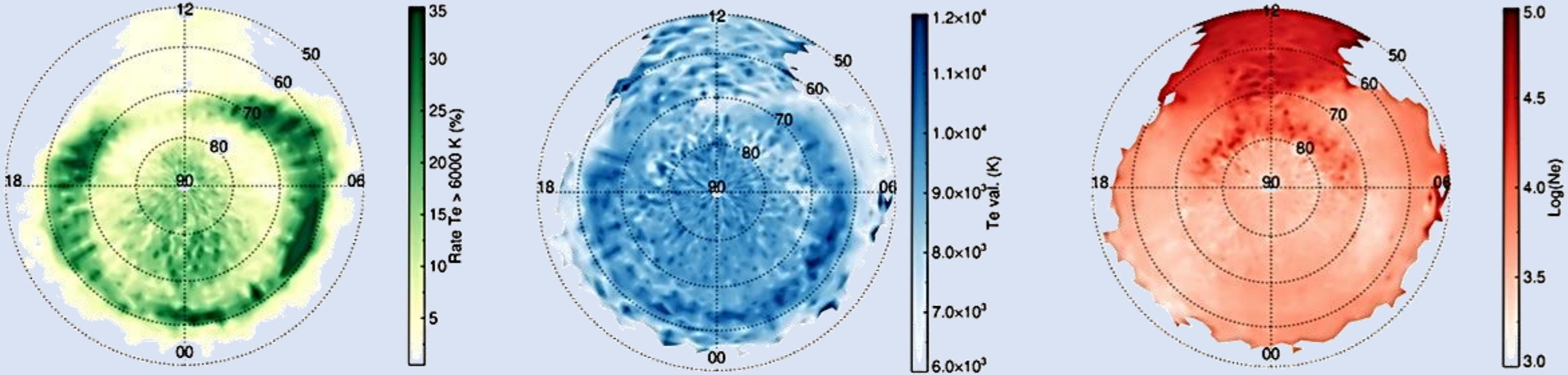
Swarm B, 2014 – 2020, Winter time

% Rate of Te > 6000 K

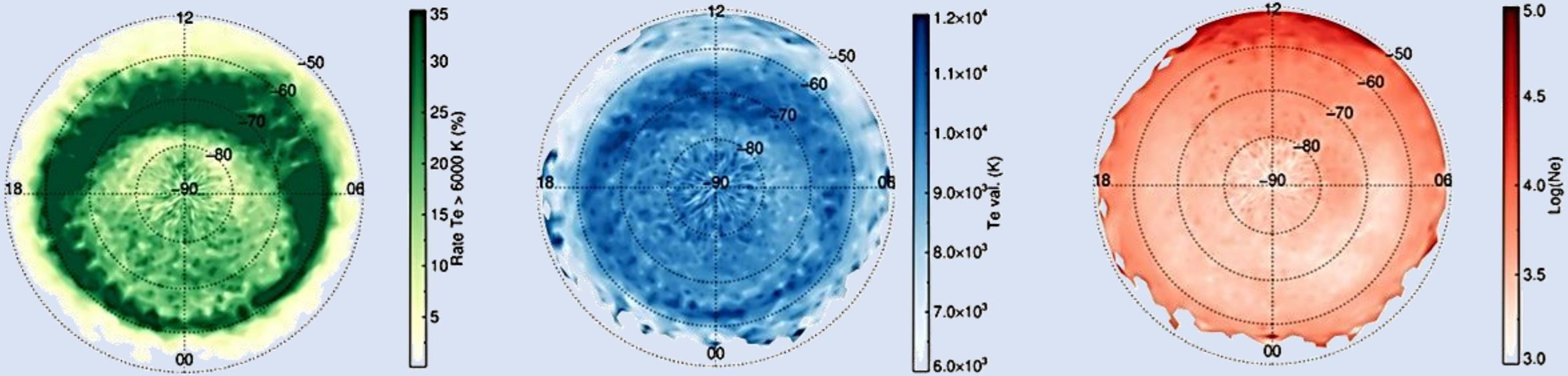
Te > 6000 K distribution

Log(Ne) distribution for Te > 6000 K

North



South



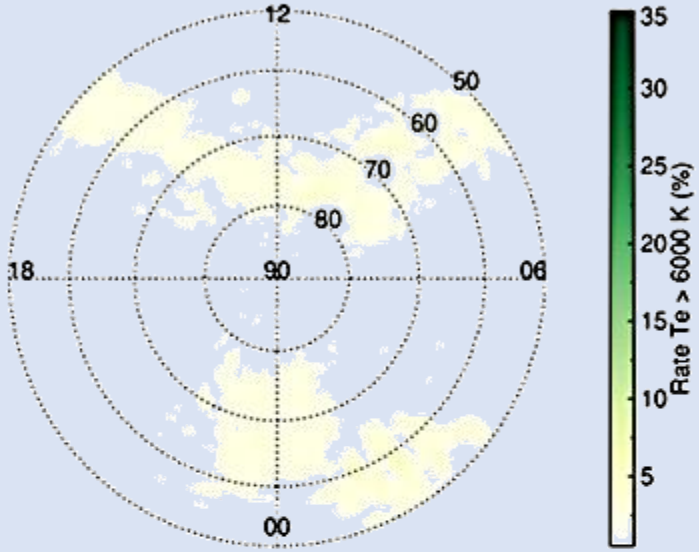
Swarm B, 2014 – 2020, Summer time

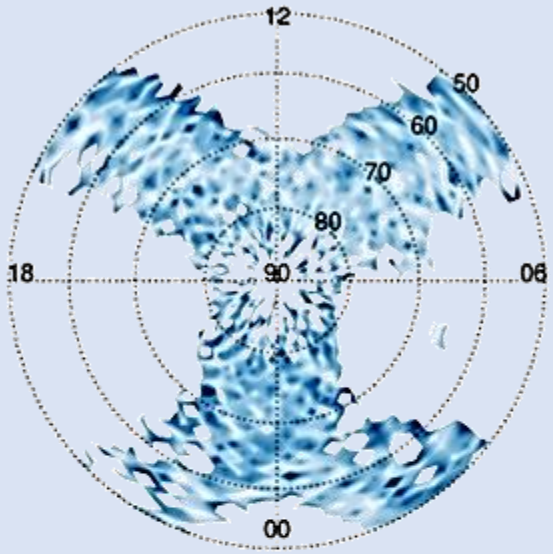
% Rate of Te > 6000 K

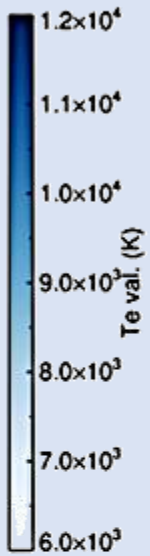
Te > 6000 K distribution

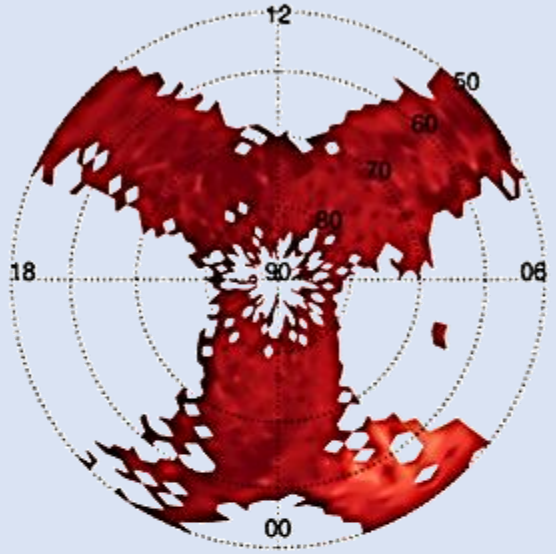
Log(Ne) distribution for Te > 6000 K

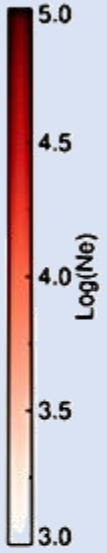
North



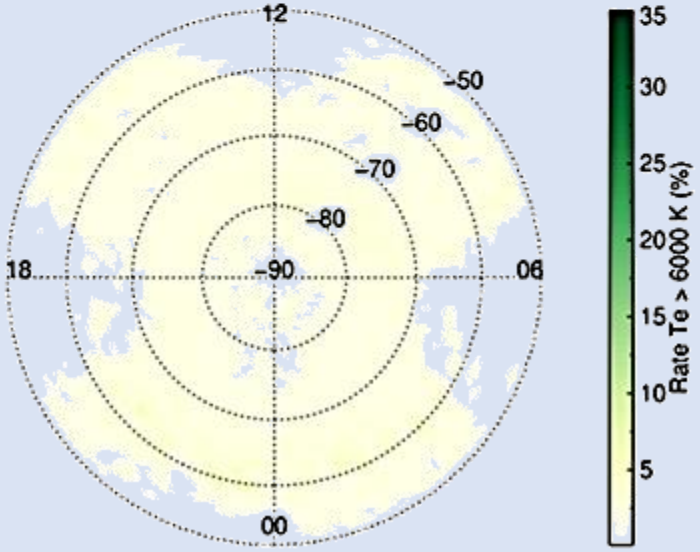


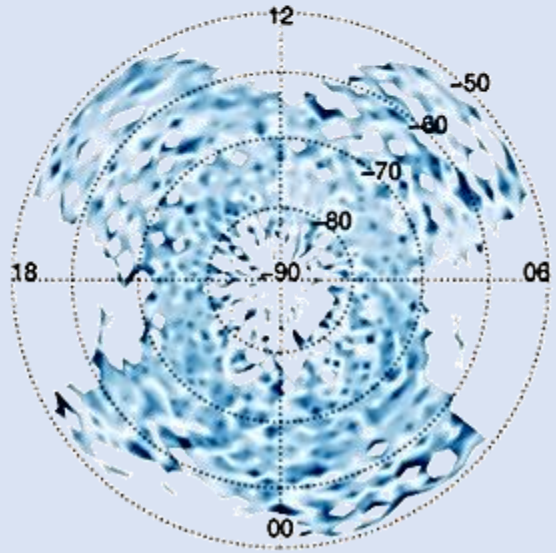


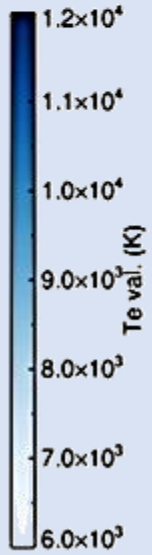


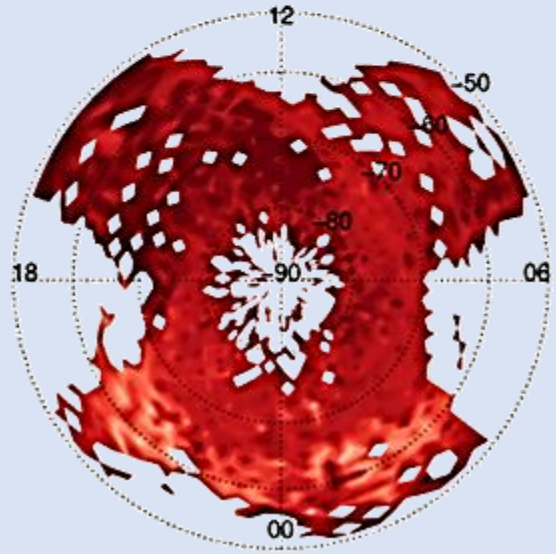


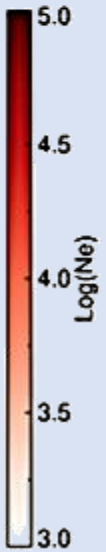
South



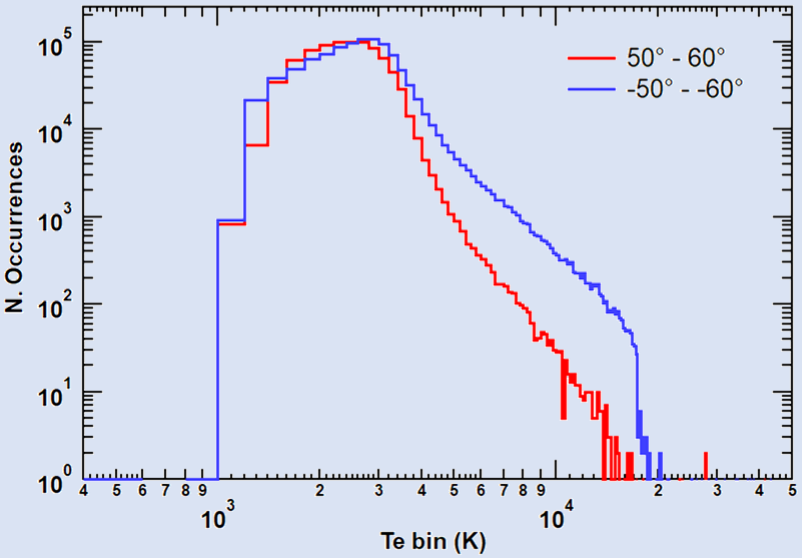


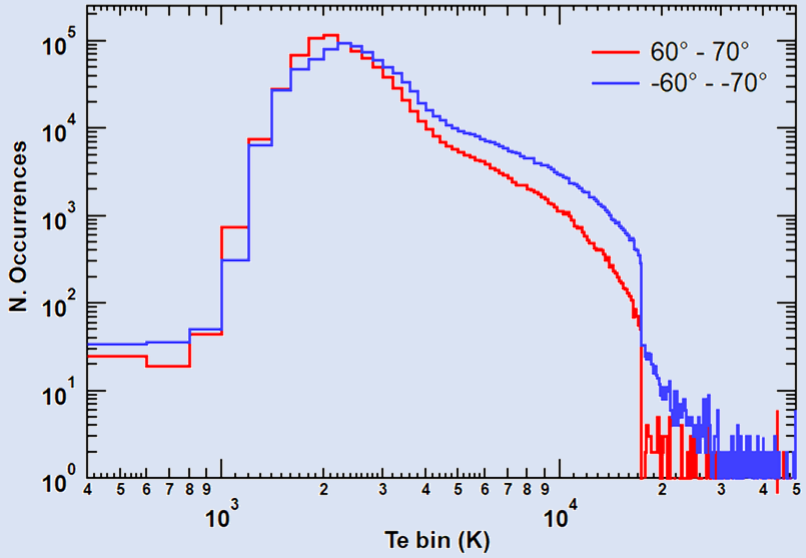


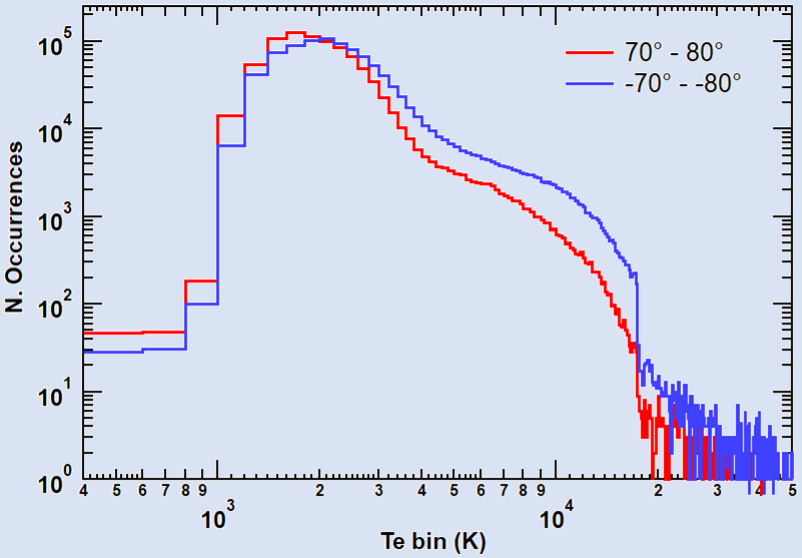


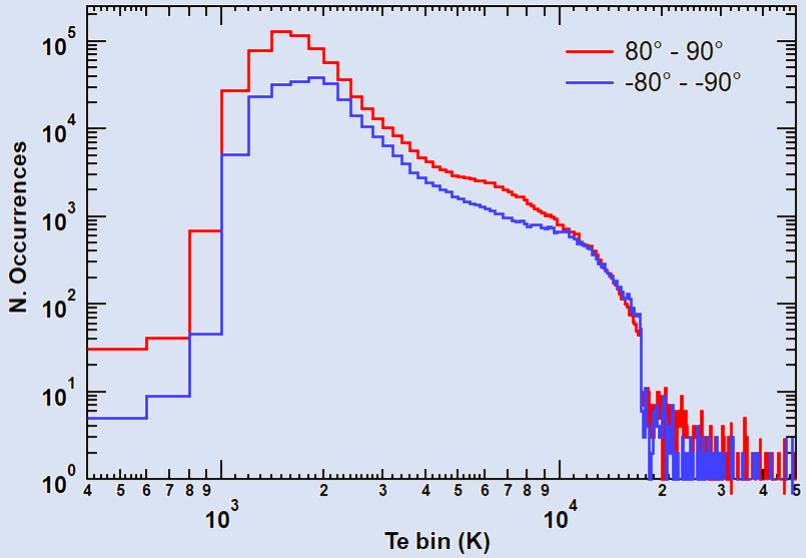


Swarm A, 2014 – 2020, Te distribution detail for winter time and 18-06 MLT









- We further limit the **winter time** distributions to the **night side (18-06 MLT)** in order to better evidence the interhemispheric differences and we display the log-log histograms of Te occurrences in bins steps of 200 K from 400 K to 50000 K, as a function of MLAT belts coupled between the two hemispheres.
- Except for very high latitudes (|80|°-|90|°) where the number of occurrences in the Northern hemisphere dominate, **in the auroral oval and subauroral regions the Southern hemisphere occurrences dominate** starting from Te > 4000 K, with the largest discrepancies observed between |50|° and |60|°.
- It is well evident the steep step where the occurrences drop down by 1-2 orders of magnitude at **17200 K**. This discontinuity is more remarkable in the Southern hemisphere, starting from -50° MLAT.

Te > 6000 K, High-Latitude distributions: Summary of the results

- As expected, Summer and Winter times distributions look very different one each other.

  - **Summer observations:** % Te > 6000 K **very low** in both hemispheres (maxima around **3-4% for Swarm B, Southern hem.**); no particular features can be spotted in both Te and Ne values distributions. High Te values are concentrated in **delimited orbit sectors** centred around the directions **9-21 and 15-3** MLT (observed distortion depends on the magnetic reference framework used).

  - **Winter observations:** % Te > 6000 K **much higher** (maxima around **38% for Swarm B, Southern hem.**) and particularly concentrated in the **auroral oval** between |60| and |75| MLAT; Te values have maxima in the same area, of about 10000-12000 K; **ion density** corresponding to high Te values is **remarkably low** (between 1000 and 5000 pp/cm^3) except in the cusp regions and at latitudes < |60| MLAT in the dayside.

- It is confirmed that the occurrence rate of high Te is higher at higher altitudes (Swarm B), and the density depletion seems also more evident at higher altitudes.

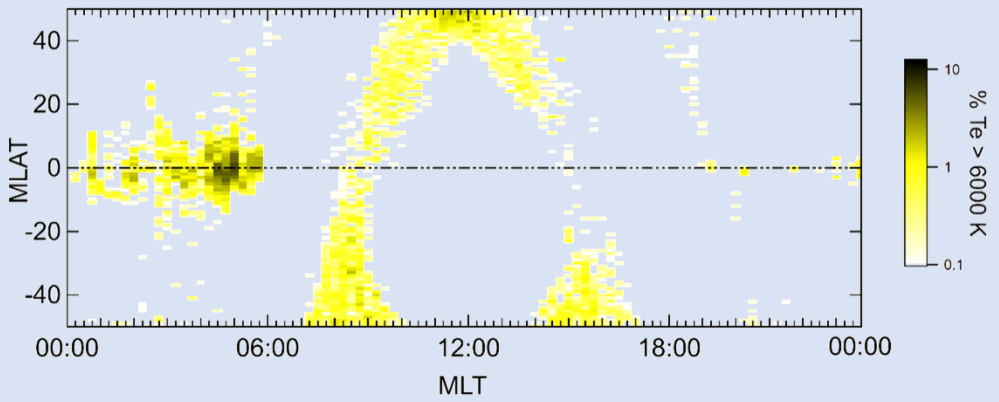
- Independently of season, the two hemispheres behave diffently: the high Te occurence is **stronger in the Southern hemisphere** than in the Northern one and extends to lower latitudes (in absolute value) in the dayside.

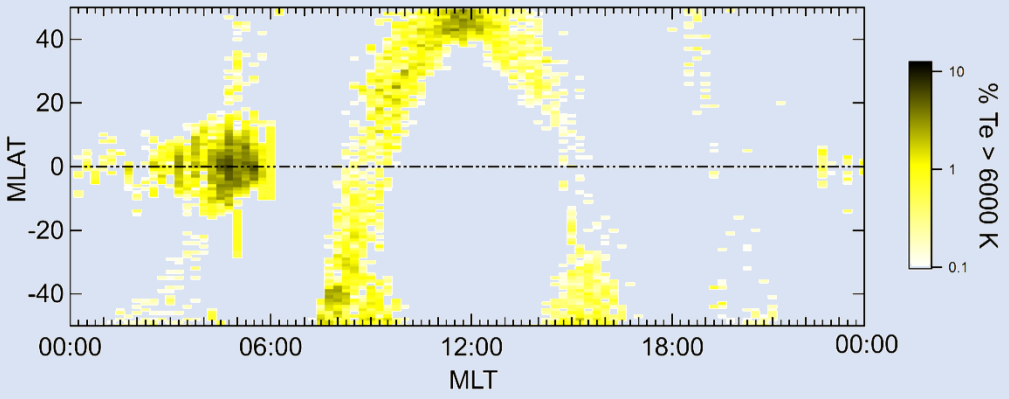
Mid-Low latitude distributions 2014-2020: December and January (North hem. winter)

Swarm A

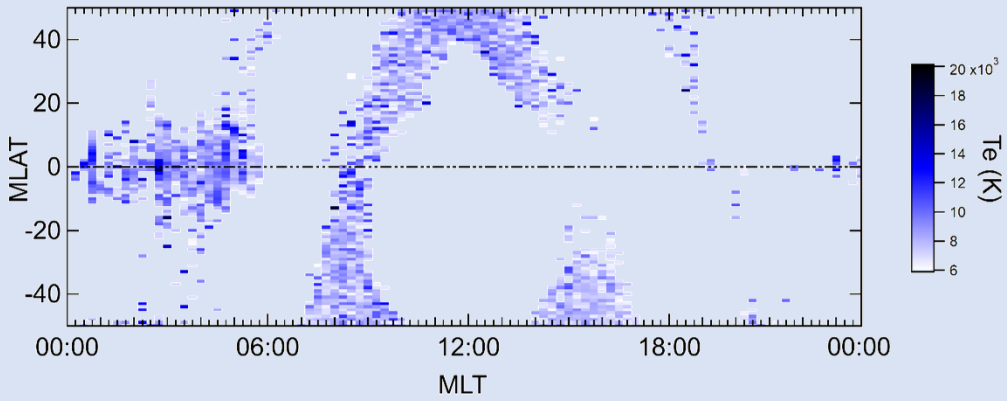
Swarm B

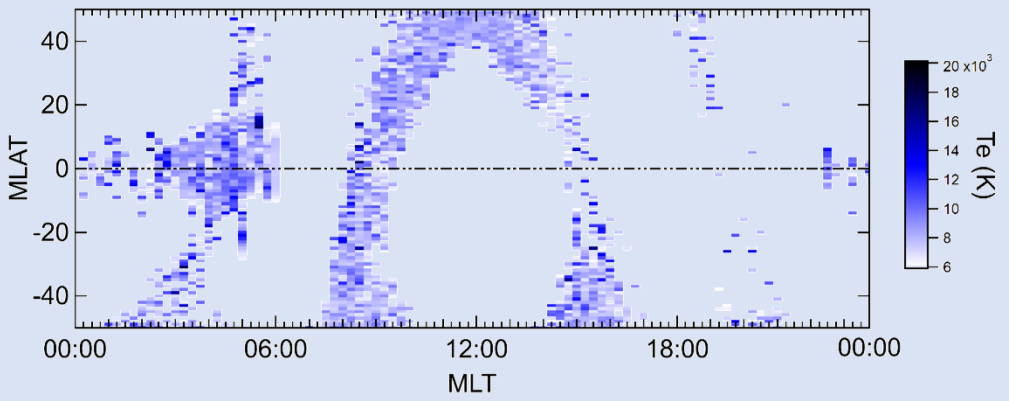
% Rate of Te > 6000 K



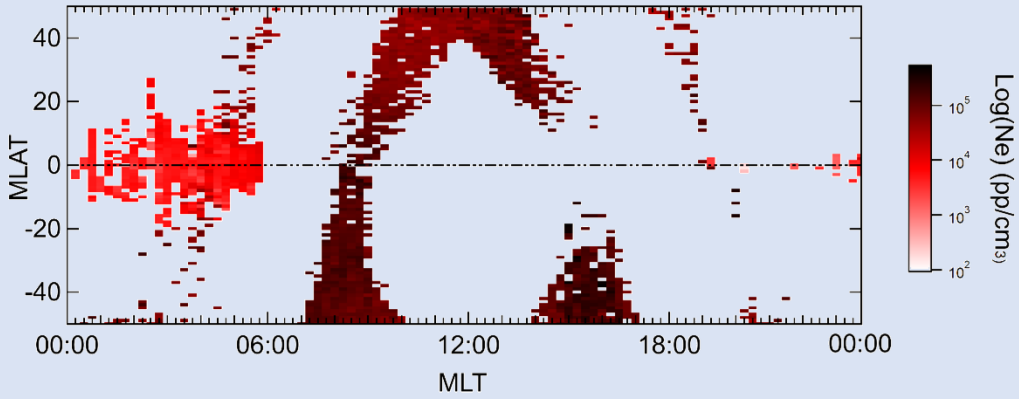


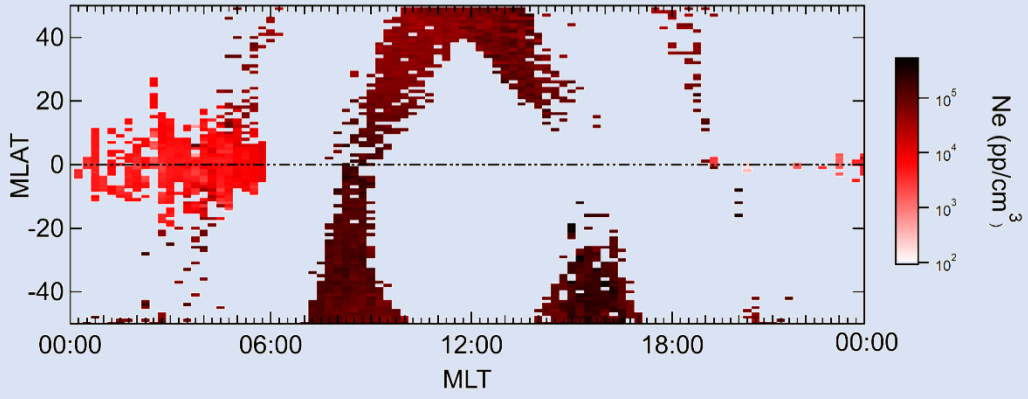
Te > 6000 K distribution





Log(Ne) distribution for Te > 6000 K



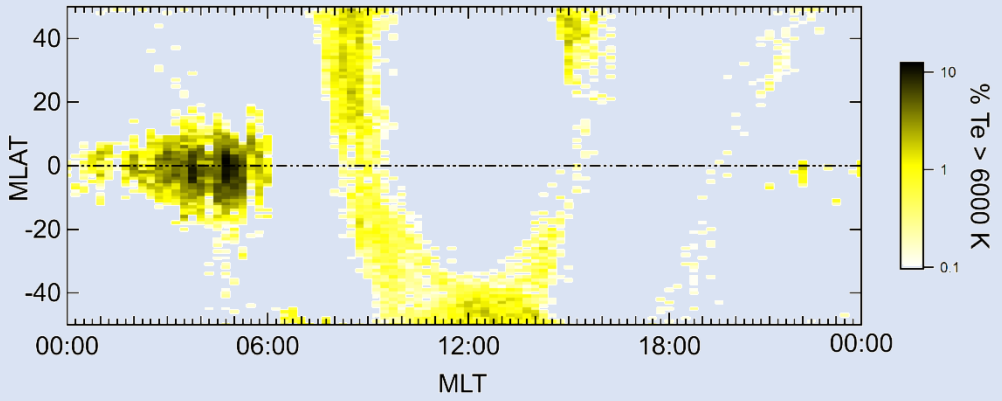


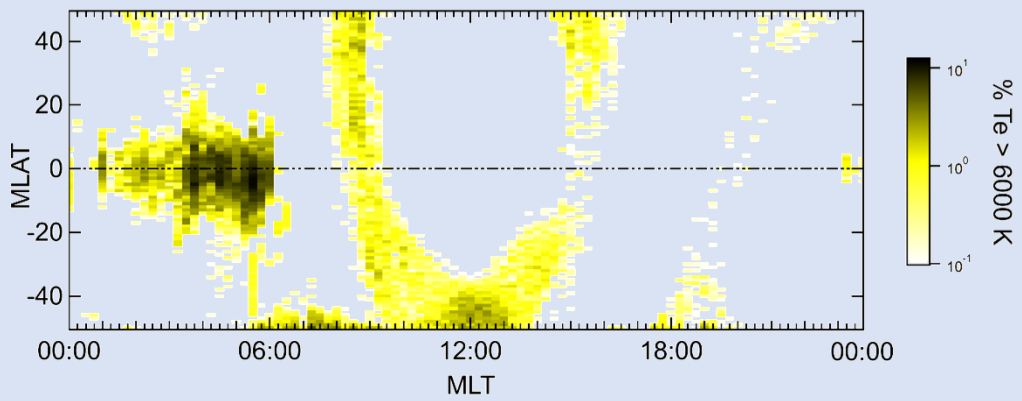
Mid-Low latitude distributions 2014-2020: June and July (North hem. summer)

Swarm A

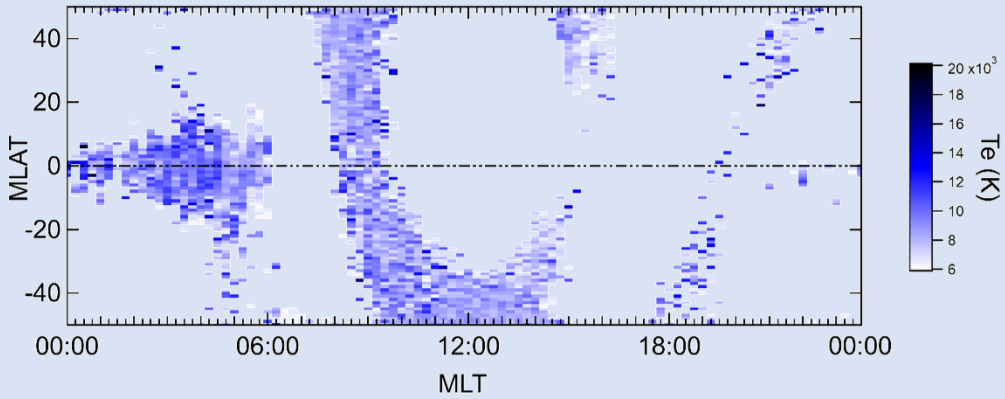
Swarm B

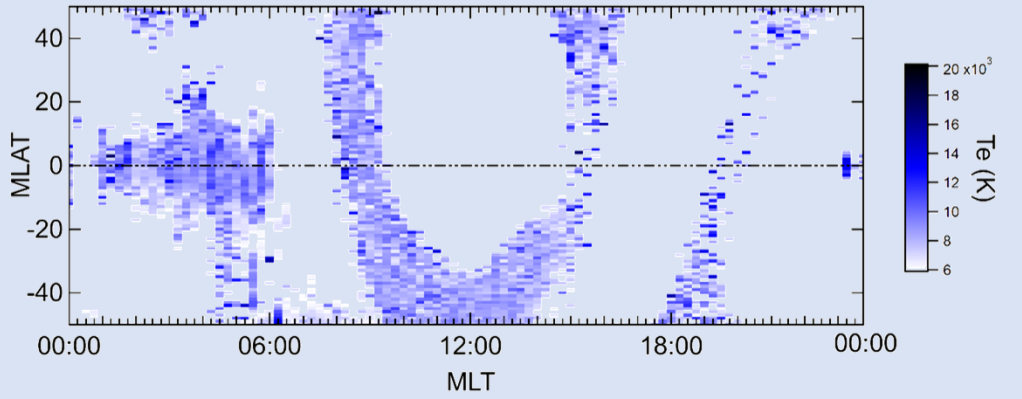
% Rate of Te > 6000 K



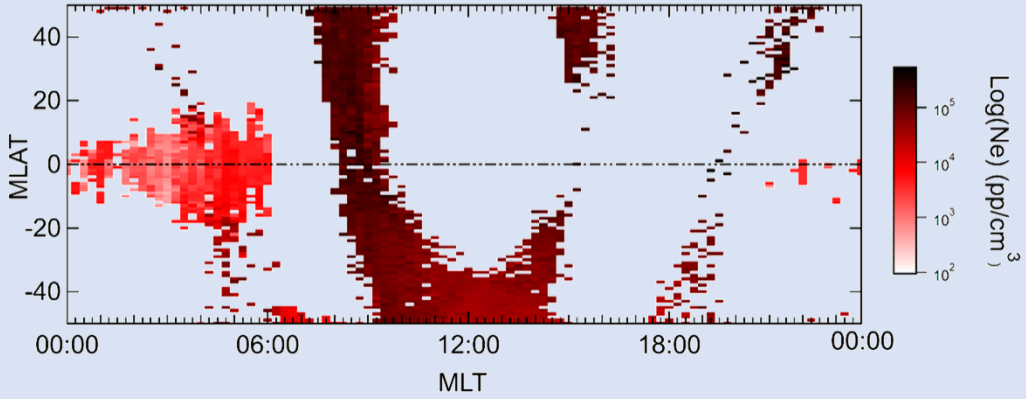


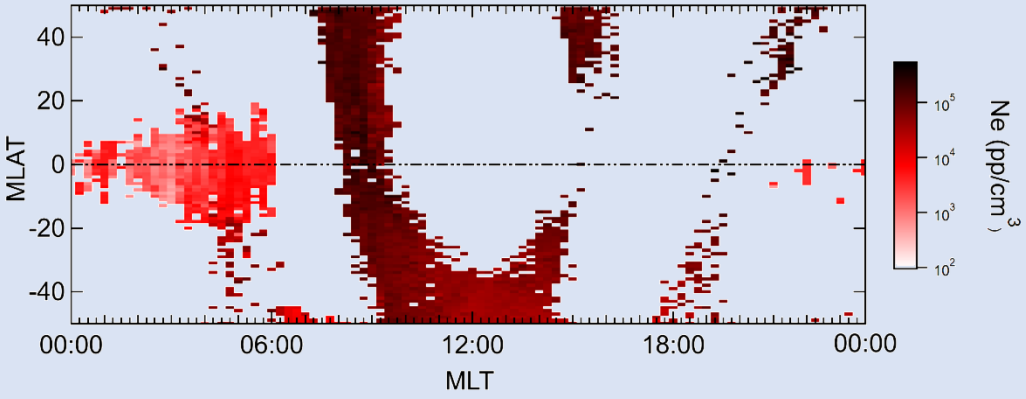
Te > 6000 K distribution





Log(Ne) distribution for Te > 6000 K





Te > 6000 K, Mid-Low Latitude distributions: Summary of the results

- Seasonal differences exist, but they are not so important in terms of occurrence rate: % of high Te is slightly greater for Summer than for Winter, with peaks of **about 10%** of the total in the **equatorial early morning sector** (the so called **«Sunrise overshoot» - SO**).

- Two distinct families of high Te emerge: **1) the SO**, where high Te values are mostly concentrated, average Te is around 10000-12000 K and, again, as for the case of the high latitudes winter times, **electron density is very low** ($< 10^4$ pp/cm^3); **2) recurrent orbital paths** around 9 and 15 MLT and other two, fainter and narrower, right before dawn and sunset, where high Te values are less numerous (few % of the total), and electron density, on average, has the magnitude expected for such latitudes.

- The shape of the orbital paths of this second population depends on season and such paths connect with the high latitude distributions of the corresponding «Summer hemisphere». The opposite hemisphere («winter hemisphere») absorbs such population in the subauroral dayside region.

- The early morning branch of the second population crosses the SO and the two populations, there, remain separated.

- Also at mid-low latitudes, the high Te occurrence is **higher at higher altitude** (Swarm B).

CONCLUSIONS AND PERSPECTIVES

- In the Swarm electron temperature high values (Te > 6000 K), two populations seem to co-exist:
  - 1) **One dominates when the spacecraft are illuminated** (summer season at high latitudes, and two distinct orbital paths at mid-low latitudes). A Swarm experts team is investigating this particular population, that seems related to a mix of intrumental and environmental effects.
  - 2) **The other dominates when the spacecraft are in shadow** (winter times at high latitudes) or in the sunrise overshoot region at the equator, and it is accompanied by electron density depletions.

- The «shadow» population is characteristic of the **auroral oval** and shows **strong interhemispheric differences**: the Southern hemisphere seems to be favoured, perhaps due to **magnetic dipole tilt effects**. Considering also the electron density depletion associated with this population, which is persistent in a height range of about 70 km (observed at both quotes of Swarm B and Swarm A-C), one could speculate that it is related to **«bursts» of intense field aligned currents** fluxes that heat plasma and pushes electrons down to lower ionospheric quotes, or lift them up above the Swarm B quotes.

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http://intens.rm.ingv.it/