Plasma-Neutral Interactions in the Lower Thermosphere-Ionosphere: The need for in situ measurements to address focused questions

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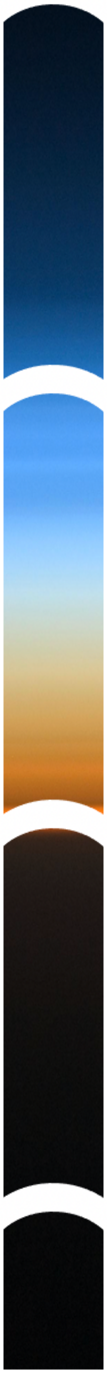

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Synopsis: The lower thermosphere-ionosphere (LTI) is a key transition region between Earth's atmosphere and space. Interactions between ions and neutrals maximize within the LTI and in particular at altitudes from 100 to 200 km, which is the least visited region of the near-Earth environment. The lack of in situ co-temporal and co-spatial measurements of all relevant parameters and their elusiveness to most remote-sensing methods means that the complex interactions between its neutral and charged constituents remain poorly characterized to this date. This lack of measurements, together with the ambiguity in the quantification of key processes in the 100 to 200 km altitude range affect current modeling efforts to expand atmospheric models upward to include the LTI and limit current space weather prediction capabilities. We present **focused questions** in the LTI that are related to the complex interactions between its neutral and charged constituents. These questions concern core physical processes that govern the **energetics**, **dynamics,** and **chemistry** of the LTI and need to be addressed as fundamental and long-standing questions in this critically unexplored boundary region. We also outline the range of in situ measurements that are needed to unambiguously quantify key LTI processes within this region, and present elements of an in situ concept based on past proposed mission concepts.

An overarching theme guiding the need for in situ measurements in the lower thermosphere - ionosphere is the need **to fundamentally advance our understanding of the energetics, dynamics, and chemistry of the atmosphere-space transition region and of the neutral-plasma interactions that shape it**. Focused science questions include:

Key question	**Path to advancement**
Q1. *How and to what extent is energy deposited as frictional heating in the LTI? How does this heating affect, and is affected by, the thermal structure, local transport, and composition within LTI altitudes?*	Measure simultaneously all the parameters relevant to frictional heating within the 100 to 200 km altitude region; characterize its variability within the high-latitude regions and at altitudes where it maximizes; relate its evolution to co-located plasma and neutral dynamics.
Q2. *What are the effects of Energetic Particle Precipitation (EPP) on the ionization and composition of the LTI? To what extent does EPP impact the mesosphere and stratosphere?*	Measure the flux of energetic charged particles traveling through the 100 to 200 km region at high latitudes to precipitate into the middle atmosphere; characterize the ionization, energy deposition and effects of EPP on conductivity in the LTI.
Q3. *What is the momentum budget in the LTI and the relative contributions of magnetospheric, solar & atmospheric forcing? What are the consequences of these forcings on fluid dynamics and electrodynamics at high, middle and low latitudes?*	Measure all parameters relevant to the LTI momentum budget across a range of latitudes and altitudes between 100 and 200 km, to discover how atmospheric and magnetospheric forcing and collisions between charged and neutral gases in the LTI affect the density, composition, winds and drifts in the region.

Q1. How and to what extent is energy deposited as frictional heating in the LTI? How does it affect, and how is it affected by, the thermal structure, local transport, and composition within LTI altitudes?

Background and motivation: Within the lower thermosphere-ionosphere region, the ionospheric plasma is forced by electromagnetic fields to convect relative to the neutral gas with consequent frictional heating **[1]**. This coupling is strongly related to solar activity. During even moderate geomagnetic storms, our present knowledge indicates, albeit with large uncertainties, that this heating source is comparable to the heat created by absorption of EUV solar radiation, which otherwise is the major driver for upper atmospheric dynamics. At moderate to strong activity, the effects of electromagnetic coupling with space are not confined to high latitudes but will propagate to the equator.

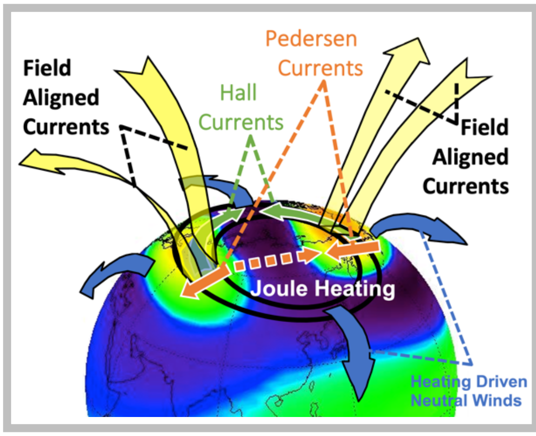

Figure 1: The closure of field aligned currents at high latitudes within the altitudes where plasma-neutral interactions maximize leads to frictional heating that subsequently modifies the neutral wind and density patterns at lower latitudes. Adapted from **[2]**.

The ways in which neutral winds, ion drifts and electric fields interact in the heating process, which maximizes in the LTI, are largely unknown, primarily due to the lack of co-located measurements of all key parameters involved. Current estimations are based on primarily ground-based measurements, which, however, only provide a subset of the required measurements that are needed to resolve frictional heating in the LTI, with limited spatial resolution, with lower accuracy compared to in situ measurements and above geographically fixed locations. Key factors affecting frictional heating include the ionospheric Pedersen conductivity, σ_P, neutral winds, u_n, electric fields, $\boldsymbol{E}$, and ion drifts, v_i. In particular, σ_P is dependent on knowledge of precipitating electrons, whereas neutral winds are affected by Lorentz forcing, both of which are poorly characterized in the LTI. Accurate estimates of σ_P and neutral wind variations in the LTI are needed for improved space weather forecasts **[3]**, and for frictional heating statistics **[4]**.

An in situ mission covering the LTI down to altitudes where plasma-neutral interactions maximize can obtain accurate estimates of frictional heating and Pedersen conductivity, that can be used to anchor ground-based observations and test current assumptions and parameterizations of frictional heating and Pedersen conductivity in models.

Broader scope: Comparisons of different models show great discrepancies by an order of magnitude or more in the amount of energy that is deposited via frictional heating in the LTI. Systematic in situ measurements will provide critically needed anchor-points that will enable its accurate representation in models. Measurements of frictional heating from different perspectives and with combinations of different measurements will enable us to test current assumptions that are used in models and estimation methods.

New data needed: In situ, co-temporal, co-spatial measurements of neutral winds, ion drifts, electric field, magnetic field, ion and neutral composition, densities and temperatures, energetic particle precipitation are needed. These measurements should be made by collecting statistically representative distributions that cover the pertinent range of auroral latitudes, local times and targeted altitudes, which lie in the 100-200 km region, and, ideally, down to the altitudes where frictional heating maximizes, which is estimated to be at ~120 km. At the same time, the altitude profile of frictional heating and its contributing parameters should be resolved, statistically and with a combination of satellite and ground-based assets.

Q2. What are the effects of Energetic Particle Precipitation (EPP) on the ionization and composition of the LTI? To what extent does EPP impact the mesosphere and stratosphere?

Background and motivation: Energetic particle precipitation (EPP) consists of energetic (keV-MeV) electrons and ions that follow the Earth's magnetic field towards the atmosphere. EPP leads to the excitation and ionization of neutrals, dissociation of molecular species, and electron temperature enhancements, all of which affect conductivity. EPP fluxes between 100 and 200 km and their contributions to key physical processes at these altitudes and below are largely unknown.

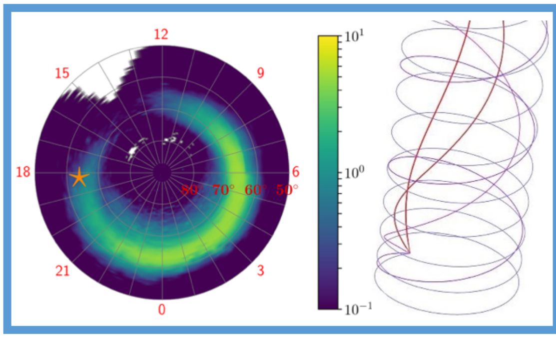

Figure 2: Left: N. hemisphere diffuse auroral electron energy flux (mW m^{-2}) based on Ovation Prime. **Right:** Simulation of particle gyro-motion for different pitch angles; Adapted from **[18]**.

The altitude of maximum energy deposition by EPP is determined by the energies of the precipitating particles. Knowledge of the energy spectrum as a function of solar and geomagnetic conditions, magnetic latitude and local time is therefore key to understanding the role of EPP within the LTI and below. Investigation of coupled-climate model runs and atmospheric reanalysis datasets have further shown that, as higher energy (>30 keV) electron precipitation passes through the LTI, it generates NO_x and HO_x at lower altitudes, leading to the catalytic destruction of ozone in the mesosphere and below **[6]**. Through the complex coupling of chemical composition changes affecting atmospheric heating and cooling rates, the mean circulation, and wave propagation and breaking, EPP also affects temperatures and dynamics of the atmosphere from the source region down to the stratosphere and possibly even down to the surface **[7]**. However, simulated altitude distributions of polar NO_x have substantial differences to those observed. One potential reason is incomplete representation of the EPP forcing and uncertainties in the formation rate of different NO_x species. Thus, EPP measurements within the LTI are also a missing link between heliophysics and lower atmosphere/Earth science.

An in situ mission obtaining, in addition to ambient ion, neutral, and field values, the spectra of EPP over the relevant energy ranges and with adequate resolution in energy and pitch angle distributions within the 100 to 200 km altitude range, would address the above gaps in the characterization of EPP and its effects in the LTI and below.

Broader scope: Energetic Particle Precipitation (EPP) impacts are currently implemented in chemistry-climate models reaching from the surface up to the mesosphere or lower thermosphere, however, there are still many open questions not only in the quantification but also in the theoretical description of the impacts of EPP. The most important issue concerns the uncertainties associated with the production rate of the different NO_x species by EPP, and the complex coupling between chemical changes, atmospheric heating and cooling rates, and atmospheric dynamics. Improved EPP measurements will lead to the improvement of the EPP specification in models **[8]**.

New data needed: Satellite-based observations of electron fluxes with high temporal, energy and pitch angle resolution within the 100 to 200 km altitude range, and coincident electric and magnetic field data so as to determine their correlation with EPP for its accurate parameterization in models.

Q3. What are the relative contributions of magnetospheric, solar and atmospheric forcing in influencing LTI fluid dynamics and electrodynamics at high, middle, and low latitudes?

Background and motivation: The presence of an ionised component (plasma) and the geomagnetic field within the LTI greatly affect the forces that drive the motion of both neutral and ion species within the region. Electromagnetic coupling introduces a direct Lorentz force to the set of forces governing the dynamics of the LTI. Currents flowing through the LTI are associated with plasma motions and co-located neutral gas motions via ion-neutral collisions. Furthermore, the LTI is the critical region where neutral dynamics, including tidal, planetary and gravity waves, drive the ionospheric dynamo and its variability in the E and bottom-F regions **[9]**. Although these processes are understood theoretically, their quantification and characterization are largely absent due to a lack of measurements in the regions where magnetospheric forcing and collisions between charged and neutral gases maximize, which is mainly within the 100 to 200 km altitude range. In particular, comprehensive measurements of neutral winds are critical in advancing current knowledge of LTI dynamics and, presently, such measurements are sparsely distributed in time and space **[10, 11]**. Furthermore, estimates of collision rates are currently based on cross-sections from ground laboratory experiments, which, however, cannot reproduce the complex LTI environmental plasma, neutral and electromagnetic conditions **[12]**. At small scales, strong flow shears and steep gradients can drive a variety of instabilities and turbulence in both plasma and neutral gas, the understanding of which is an outstanding challenge in space physics community. Instabilities and turbulence, in turn, result in irregularities of various scales, which have practical implications for the propagation of waves. In particular, variations and gradients in the plasma density can strongly affect the propagation of trans-ionospheric radio waves on which our modern communication and navigation systems rely.

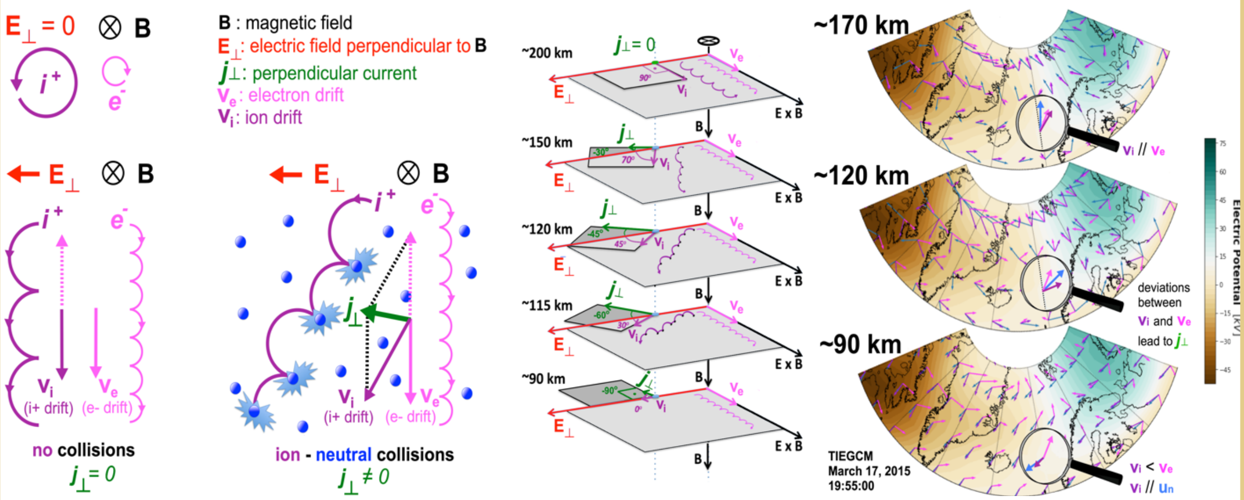

Figure 3: Ion and electron (**E×B**) drifts in the frame of the neutral gas as a function of altitude (i.e. neutral density & number of collisions), and resulting electric currents [*fig: T. Sarris*]

An in situ mission that samples with high cadence the physical properties of the charged and neutral gas alongside electromagnetic fields within the 100-200 km altitude region, where collisions between charged and neutral particles maximize, would close the gaps in our understanding of the dynamics and its electrodynamic coupling on relevant scales

Broader scope: No current or prior set of observations combines simultaneous and co-spatial measurements of horizontal and vertical neutral winds together with electric currents. These are needed in many fundamental quantities without which the LTI physics cannot be represented. For example, they are required to define the poorly known ion-neutral collision frequencies, which constitute a long-standing knowledge gap in the understanding of LTI dynamics. Furthermore, the processes associated with atmospheric waves, their propagation, and their local and global effects on LTI dynamics remain enigmatic. These are knowledge gaps that an in situ mission which samples the LTI below 200 km will be able to fill. Knowledge of the above processes is critical for current and future models and will also be useful in understanding the atmospheric super-rotation in the ionospheres of Venus and Titan, where ion motion is consistent with but faster than the super-rotation of the neutral atmosphere.

New data needed: Satellite-based, in situ, co-temporal and co-spatial measurements of neutral winds, ion drifts, electric field, magnetic field, ion and neutral composition, densities and temperatures in the 100 to 200 km altitude range are needed.

Current status of in situ measurements below 200 km: The only systematic in situ spacecraft observations within the 100-200 km region to date were made by the Atmosphere Explorer AE-C, AE-D, and AE-E satellites (1973–1981), which measured density, ion drifts, neutral and ion composition and temperatures along elliptical orbits, achieving measurements down to a lowermost altitude of 128 km by use of propulsion. However, as shown in **Figure 4**, the total observation time from the three missions combined is only ~60 hours below 200 km, with a much smaller subset of this time allocated to high latitudes, the theater of key LTI processes. At the same time, AE spacecraft lacked neutral wind, electrodynamics and energetic particle measurements, and the interpretation of some critical measurements, such as mass spectrometer composition data, proved difficult at low altitudes. The Dynamics Explorer DE-2 satellite (1981–1983) included also measurements of energetic particles, electric field and neutral winds; however DE-2 did not include propulsion and the lowermost altitudes sampled were above 250 km. In the absence of other systematic co-temporal and co-spatial measurements, sounding rockets have proved to be an invaluable means to obtain in situ measurements in the LTI, however, by nature, they are limited by providing only a snapshot of an altitude profile and most often carry limited instrumentation.

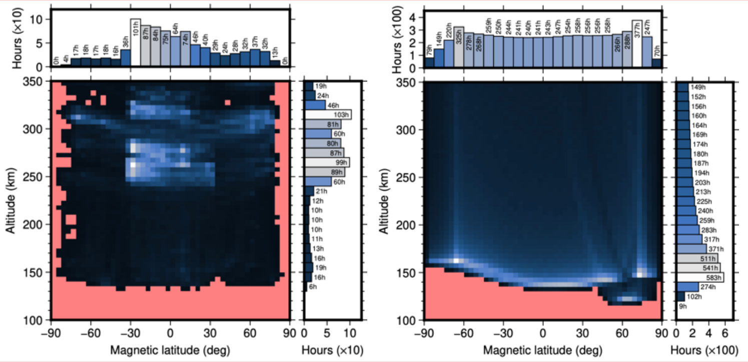

Figure 4: Left: Total observation time from AE-C, AE-D and AE-E combined, as a function of altitude and magnetic latitude. Total observation time at altitudes below 200 km is 60.3 hours (Unified Abstract data). **Right:** Targeted total observation time from a 3-year in situ mission dedicated to studying LTI processes: ~2000 hrs at altitudes < 200 km. Deep-dips (perigee descents) according to this concept are performed down to 120 km when perigee is over high latitudes. (fig. by E. Doornbos; adapted from **[18]**).

Notional concept for a space mission to sample the LTI below 200 km: Since the time of the Atmosphere Explorers, there have been a number of matured mission concepts highlighting the need to sample plasma-neutral interactions at altitudes below 200 km with a fully instrumented satellite. These include: (a) the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission concept as originally proposed, and in particular the descoped in situ components of the twin-spacecraft mission, labeled TIMED-H and TIMED-L **[13]**; (b) the Geospace Electrodynamic Connections (GEC) mission concept **[14, 15]** (not to be confused with the Geospace Dynamics Constellation (GDC) mission concept **[16]**, currently being selected for Phase A studies, which targets altitudes at 350 km or higher); (c) the Atmosphere-Space Transition Region Explorer (ASTRE) mission concept **[17]**; (d) the Daedalus mission concept **[18, 19]**. These mission concepts promise to offer an order-of-magnitude or more measurements than are currently available, as shown in the right panel of **Figure 4** for the Daedalus mission. MAVEN, an active Mars mission, successfully performs measurements in the Martian thermosphere–ionosphere **[20]**; such measurements are still lacking at the Earth's upper atmosphere. In the following, we outline the striking commonalities between these mission concepts that point to the notional concept of an in situ mission targeting to study plasma-neutral interactions in the LTI at altitudes below 200 km.

Since circular orbits below 200 km are short-lived by nature due to atmospheric drag, a common component of all the above mission concepts is that the in situ sampling scheme is performed along elliptical orbits. Apogee altitudes of 1500 km were baselined for TIMED-L and ASTRE, and 2000 km or above for TIMED-H, GEC and Daedalus. Nominal perigee altitudes ranged from 150 km (TIMED-H, TIMED-L, Daedalus) to 185 km (GEC) and 285 km (ASTRE). MAVEN also sampled the Martian upper atmosphere from elliptical orbits. By laws of orbital dynamics, elliptical orbits lead to perigee and local time precession, allowing sampling of perigee altitudes at both high and low latitudes and of extended local times. For sampling altitudes below the nominal perigee, all the above mission concepts make use of propulsion to episodically lower perigee, a maneuver that has been called a "deep-dip" or "deep-dive". The lowermost altitudes targeted by the above concepts are all below 200 km: TIMED-H, TIMED-L and Daedalus target measurements down to 120 km, GEC targets 130 km "and possibly lower", and ASTRE aims to perform measurements "below 200 km". Another striking similarity across the above mission concepts, highlighting the optimal path towards conclusively resolving processes related to plasma-neutral interactions in the 100-200 km transition region, is the need for comprehensive measurements of all parameters involved; thus, the instrument suites of all missions include in situ measurements of neutral winds, ion drifts, electric-magnetic fields, ion-neutral composition, densities and temperatures, and EPP.

Multi-point measurements: Several of the above mission concepts have highlighted the substantial additional benefits of multi-point measurements: beyond significantly enhancing coverage, a second spacecraft can bring about estimation of gradients, shears and altitude profiles, or space-time effect disambiguation. For example, it has been demonstrated how simultaneous measurements at two altitudes by identically instrumented satellites enable determining altitudinal gradients or profiles of electron density, Pedersen conductivity and Joule heating directly, rather than statistically **[21]**. A concept has been proposed where nano-satellites in the form of CubeSats are deployed from a mothership **[18]**; these can be used as reference points or "buoys" for the estimation of local gradients of key properties while the mothership dips down to lower altitudes. Other concepts such as GEC emphasize the need for multi-point measurements in a "pearls-on-a-string" and "petal" configuration, addressing, respectively, spatial/temporal scales and exploring spatial extent of processes **[14]**. It is noted that the mission concepts involving multi-spacecraft observations emphasize the possibility of modifying the orbital configurations at different phases of the mission, to address different aspects of spatial and temporal characteristics of LTI processes.

Notional "way forward" including technology development needs: Based on heritage from the early AEs of the 1970's and from the NASA and ESA studies listed above, an in situ mission to sample the lower thermosphere-ionosphere to perigee passes of at least 120 km is entirely feasible. Since the 1970's, early generations of instruments covering all required parameters have been flown successfully within the LTI region (80-200 km) on sounding rockets (with nominal velocities of ~1 km/s), however, comprehensive measurements of the region will require coverage from orbit. For some measurements, this demands a new generation of measurement techniques capable of coping with non-geophysical perturbations, such as shock-induced variations and sputtered ions from the spacecraft surfaces at the lowermost altitudes. Fortunately, well-established techniques exist to model and address such satellite-generated disturbances and can be studied to mitigate these concerns. Given that satellite drag and re-entry considerations become a concern below 120 km, and due to the tremendous scientific return promised from such an unprecedented low perigee mission, we strongly urge that a satellite be flown as soon as possible with instruments to measure all of the relevant parameters to altitudes as low as 120 km; measurements below 120 km can be carried out on an exploratory basis during an extended mission phase based on findings from initial low perigee excursions to 120 km. The mission promises to open a new world of understanding of how the lower thermosphere and ionosphere works as a system, addressing all of the major outstanding questions outlined above.

Summary: The focused questions presented here argue strongly for an in situ mission to sample the lower thermosphere - ionosphere in the coming decade, to address critical, yet unquantified processes related to plasma-neutral interactions in the transition region from the neutral atmosphere to plasma-dominated space. A satellite equipped with instruments to provide co-located measurements of ion drifts, neutral winds, electric and magnetic fields, ion and neutral density, composition and temperature, and energetic particle precipitation is anticipated to yield a wealth of crucially lacking information, which will support a broad range of advances in atmospheric and space sciences. These measurements will enable the accurate quantification of frictional heating, the specification of which is currently a major challenge in global circulation models. Accurate estimates of ionospheric conductivity will lead to improvements in magnetospheric models, as conductivity specification determines, among others, the closure of currents, the evolution of magnetospheric and ionospheric dynamics, the convection state, and the timing and strength of auroral substorms. Measurements within this region will lead to improvements of whole atmosphere models that include the LTI. Data assimilation using these new datasets will help improve numerical models. Better understanding and parameterizations will improve predictions of drag effects and spacecraft re-entry. In situ measurements of perpendicular electrical currents and magnetospheric forcing will provide insights on their relationship and will improve our understanding of the cause of Geomagnetically Induced Currents, a significant Space Weather threat. Measurements within this region will also assist in additional topics, not described above, such as in improving satellite-level gas-surface interaction modelling algorithms and assumptions, enhancing existing models of Earth's global lithospheric magnetic fields at medium to small scales, and investigating the interaction of particles with electromagnetic waves.

An in situ mission based on a single spacecraft can achieve all of the above objectives. However, beyond significantly enhancing coverage, simultaneous measurements by a second spacecraft at a different altitude would enable the estimation of gradients, shear and altitude profiles; measurements by a second spacecraft in a "pearls-on-a-string" configuration would enable differentiating between temporal and spatial effects; and measurements by a second spacecraft on a "petal" configuration would enable exploring the latitudinal extent of processes.

In conclusion, a mission that provides in situ measurements down to altitudes where ion-neutral interactions maximize (120 km or lower) of ion drifts, neutral winds, electric and magnetic fields, ion and neutral density, composition and temperature, and pitch angle-resolved energetic particle precipitation is feasible and mature. This will allow us to explore and investigate, for the first time, the dominant processes that determine the energetics and dynamics in the atmosphere-space transition region. Such a mission will provide the first simultaneous and comprehensive set of measurements of all physical quantities that are needed to reveal fundamental processes involving the coupling of ionized and neutral gases. Measurements in the heart of the under-sampled atmosphere-space transition region are key toward future advances in modeling the lower/middle/upper atmosphere - ionosphere - magnetosphere as a multi-coupled system.

This mission can be paired with longer-term ground-based remote-sensing measurements, such as with SuperDARN and EISCAT_3D, to provide context measurements and a telescope-microscope view across multiple scales; this mission can also be paired with upcoming missions such as GDC **[16]** that will sample the 300 to 400 km altitude range, significantly above the altitude ranges of interest targeted herein, and DYNAMIC **[20]**, that will provide a more global perspective of the neutrals in the lower thermosphere.

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